CONTROLLING HAZARDOUS NOISE AND DUST WITHIN THE INDUSTRIAL WORKFORCE USING A SIMPLE BARRIER

THESIS

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Abstract

The United States Air Force (USAF) has experienced a dramatic increase in hearing loss claims since 2001. Additionally, many operations within the USAF expose personnel to hazardous dust levels. Likewise, the US mining industry has difficulties controlling hazardous noise and dust exposures in underground mining. Specifically, studies have shown that coal mine longwall shearer operators are routinely exposed to noise levels at 151 percent of the allowable dose and approximately 20 percent exceed regulatory dust levels. An above ground full scale model of the underground shearing operation was developed to test the feasibility of mounting a permanent partial barrier on the longwall shearer. The barrier was constructed and tested at the National Institute for Occupational Safety and Health Pittsburgh Research Laboratory (NIOSH-PRL) longwall test facility. The barrier achieved as high as a 7.3 dB(A) reduction in noise levels and a 96 percent reduction in respirable dust. Several predictive models were tested and compared to measured noise reduction results. A final spreadsheet was developed as a tool for base level Bioenvironmental Engineers to determine when a partial barrier may be an effective engineered solution for controlling hazardous noise or dust within USAF industrial operations.

To the industrial worker exposed to hazardous noise and dust

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Daniel D. Sweeney

Table of Contents

Page
Abstract iv
Acknowledgements vi
Table of Contents vii
List of Figures ix
List of Tables xii
1. Introduction 1
Background 1
Noise 1
Dust 6
Problem Statement 7
Research Focus 8
Methodology 9
Assumptions/Limitations 10
2. Literature Review 10
Noise 10
Dust 13
3. Methods 15
Pilot Study 15
Tests Performed at Wright Patterson Air Force Base (WPAFB) 15
Sound Reproduction at the WPAFB Test Facility 15
Partial Barrier Test at the WPAFB Test Facility 17
Sound Intensity Measurement 18
Room Absorption Coefficient 19
Calculation of Noise Reduction from a Partial Barrier 20
Testing at the NIOSH-PRL Facility 22
Barrier Construction 22
Sound Testing 25
Dust Testing 27
4. Results 29
Tests Performed at WPAFB 31
Sound Reproduction at the WPAFB Test Facility 31
Sound Measurement at the WPAFB Test Facility 32
Sound Intensity Measurement 34
Room Absorption Coefficient 35

Page

Calculations 36
Testing at the NIOSH-PRL Facility.. 38
Sound Testing 38
Dust Testing...40
5. Discussion...42
WPAFB Sound Tests 42
NIOSH-PRL Sound Tests 44
NIOSH-PRL Dust Tests... 46
Additional Noise Barrier Modeling 47
6. Conclusions..49
Appendix A..51
Appendix B..53
Appendix C..77
Appendix D..97
Appendix E: Decision Matrix Worksheet…………………………………..Electronic File
Bibliography 100
Vita 103

List of Figures

Page
Figure 1: Ear hair cells can be destroyed by chronic noise exposure 2
Figure 2: The number of new major hearing loss claims from Air Force veterans. 4
Figure 3: Misuse of HPDs can drastically reduce effectiveness. 5
Figure 4: Audio equipment configuration at WPAFB test facility 16
Figure 5: Placement of OBA from source 18
Figure 6: Sound intensity probe locations 19
Figure 7: Diffracted sound path over barrier 21
Figure 8: Ceiling noise reflection path.. 22
Figure 9: Mock longwall shearer with: A: No barrier and B: The partial barrier............ 24
Figure 10: Barrier mounted on mock-shearer 24
Figure 11: Four barrier configurations tested for noise reduction 25
Figure 12: A: Speaker location at headgate drum and B: Sound meter on tripod 25
Figure 13: Partial and full noise barriers.. 26
Figure 14: Simulated full scale longwall facility at NIOSH-PRL 28
Figure 15: Suspended RAM.. 29
Figure 16: Frequency response of reproduced shearer noise vs. MSHA recorded noise. 32
Figure 17: Frequency measurements with and without plywood barrier 33
Figure 18: Mean sound level reduction for plywood barrier 34
Figure 19: Sound reduction for center octave band analysis 38
Figure 20: Example of noise reduction from the various barrier configurations............. 39
Figure 21: Respirable dust levels for low, medium, and high relative face velocities 41
Figure 23: View of headgate cutting drum through partial barrier 42
Figure 24: WPAFB test configuration 44
Figure 25: Model for NIOSH-PRL headgate position, 50% male................................... 48

Figure A 1: Front view of audio equipment... 51
Figure A 2: Rear view of audio equipment.. 52

Figure B 1: Recorded shearer noise at simulated headgate position 53
Figure B 2: Recorded shearer noise at simulated center position.................................... 54
Figure B 3: Recorded shearer noise at simulated tailgate position.................................. 55
Figure B 4: Pink noise at simulated headgate position 56
Figure B 5: Pink noise at simulated center position 57
Figure B 6: Pink noise at simulated tailgate position 58
Figure B 7: Octave band analysis headgate drum, recorded noise - 5% female............... 59
Figure B 8: Octave band analysis headgate drum, recorded noise - 50% male................ 60
Figure B 9: Octave band analysis headgate drum, recorded noise - 95% male................ 61
Figure B 10: Octave band analysis center position, recorded noise - 5% female............. 62
Figure B 11: Octave band analysis center position, recorded noise - 50% male.............. 63
Figure B 12: Octave band analysis center position, recorded noise - 95% male.............. 64
Figure B 13: Octave band analysis tailgate position, recorded noise - 5% female........... 65

Page

Figure B 14: Octave band analysis tailgate position, recorded noise - 50% male............ 66
Figure B 15: Octave band analysis tailgate position, recorded noise - 95% male............ 67
Figure B 16: Octave band analysis headgate position, pink noise - 5% female 68
Figure B 17: Octave band analysis headgate position, pink noise - 95% male 69
Figure B 18: Octave band analysis headgate position, pink noise - 95% male 70
Figure B 19: Octave band analysis center position, pink noise - 5% female.................... 71
Figure B 20: Octave band analysis center position, pink noise - 50% male..................... 72
Figure B 21: Octave band analysis center position, pink noise - 95% male..................... 73
Figure B 22: Octave band analysis tailgate position, pink noise - 5% female.................. 74
Figure B 23: Octave band analysis tailgate position, pink noise - 50% male................... 75
Figure B 24: Octave band analysis tailgate position, pink noise - 95% male................... 76

Figure C 1: Oneway analysis of sound level by barrier configuration 78
Figure C 2: Oneway analysis of sound level by barrier configuration sound type=pink, position=center, operator height=low 79
Figure C 3: Oneway analysis of sound level by barrier configuration sound type=pink, position=center, operator height=medium 80
Figure C 4: Oneway analysis of sound level by barrier configuration sound type=pink, position=center, operator height=high 81
Figure C 5: Oneway analysis of sound level by barrier configuration sound type=pink, position=headgate, operator height=low... 82
Figure C 6: Oneway analysis of sound level by barrier configuration sound type=pink, position=headgate, operator height=medium 83
Figure C 7: Oneway analysis of sound level by barrier configuration sound type=pink, position=headgate, operator height=high 84
Figure C 8: Oneway analysis of sound level by barrier configuration sound type=pink, position=tailgate, operator height=low 85
Figure C 9: Oneway analysis of sound level by barrier configuration sound type=pink, position=tailgate, operator height=medium 86
Figure C 10: Oneway analysis of sound level by barrier configuration sound type=pink, position=tailgate, operator height=high 87
Figure C 11: Oneway analysis of sound level by barrier configuration sound type=recorded, position=center, operator height=low 88
Figure C 12: Oneway analysis of sound level by barrier configuration sound type=recorded, position=center, operator height=medium 89
Figure C 13: Oneway analysis of sound level by barrier configuration sound type=recorded, position=center, operator height=high 90
Figure C 14: Oneway analysis of sound level by barrier configuration sound type=recorded, position=headgate, operator height=low 91
Figure C 15: Oneway analysis of sound level by barrier configuration sound type=recorded, position=headgate, operator height=medium 92

Page

Figure C 16: Oneway analysis of sound level by barrier configuration sound type=recorded, position=headgate, operator height=high 93
Figure C 17: Oneway analysis of sound level by barrier configuration sound type=recorded, position=tailgate, operator height=low... 94
Figure C 18: Oneway analysis of sound level by barrier configuration sound type=recorded, position=tailgate, operator height=medium.. 95
Figure C 19: Oneway analysis of sound level by barrier configuration sound type=recorded, position=tailgate, operator height=high.. 96

Figure D 1: WPAFB Headgate Position 97
Figure D 2: WPAFB tailgate position... 97
Figure D 3: NIOSH-PRL headgate position, 50% male, barrier configuration D............ 98
Figure D 4: NIOSH-PRL center position, 50% male, barrier configuration D 98
Figure D 5: NIOSH-PRL tailgate position, 50% male, barrier configuration D 99

List of Tables

Page

Table 1: Outline of hypotheses tested 8
Table 2: Relative face velocities for each configuration 29
Table 3: Outline of hypotheses results 30
Table 4: Sound intensity measurements for the headgate speaker 35
Table 5: Sound intensity measurements for the tailgate speaker 35
Table 6: TA at WPAFB test facility 36
Table 7: Calculated sound levels with the barrier in place 36
Table 8: Actual versus measured insertion loss 37
Table 9: Measured TA at NIOSH-PRL test facility 40
Table 10: Predicted vs. measured IL using measured TA 43
Table 11: Measured versus predicted loss using simplified model 48

Table A 1: Initial audio equipment settings 51
Table A 2: Mode switch configuration for amplifiers 52

Table C 1: Barrier test at WPAFB test facility headgate position 77
Table C 2: Barrier test at WPAFB test facility tailgate position 77

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1. Introduction

Background

Noise

Hearing is such a valuable sense to ordinary living; it can rarely be appreciated for all the value it adds to our lives. As stated in one of the fundamental books on hazardous noise, *The Noise Manual*, “hearing is fundamental to language, communication, and socialization” (Berger, 2003). Thus, those who experience degraded hearing often have decreased quality of life. Hearing is so critical to everyday life, and loss of hearing can leave the individual feeling socially isolated. In Berger’s example, the common phrase “are you deaf” often has little to do with one’s ability to hear, but rather is the person socially inept. Furthermore, hearing loss not only affects the individual, but family and friends as well, often making conversation difficult and straining relationships.

Noise Induced Hearing Loss (NIHL) is a permanent disabling condition induced from chronic exposure to high levels of noise. Hearing loss from excessive noise exposure is caused by degeneration of the nerve fibers associated with the hair cells of the inner ear (Fig 1).

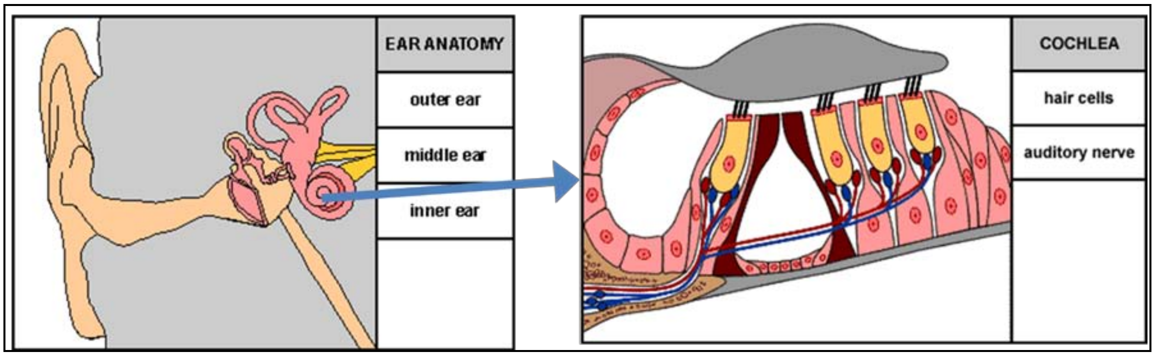


Figure 1: Ear hair cells can be destroyed by chronic noise exposure **(CHPPM, 2006)**

Once the damage has occurred, the hair cells cannot regenerate (Bruce, Bommer, & Moritz, 2003). Although it is commonly believed hearing aids can be used to overcome the loss, if the loss is from nerve damage, the hearing aid can only partially restore hearing ability (Berger, 2003). Reported as being even worse than the hearing loss itself, is a condition known as tinnitus, which is a constant high-pitch ringing in the ears. Tinnitus is "the most prevalent disability among new cases added to Veterans' Affairs rolls" (CHPPM, 2003).

Within the United States, 30 million people are occupationally exposed to hazardous noise causing nearly all of the 10 million people who currently suffer from NIHL. Additionally, NIHL increased 26 percent from 1971 to 1990 among individuals between 18 to 44 years old(Stephenson & Stephenson, 2000).

On 10 January, 1989, the Department of Defense (DoD) authored instruction (DoDI) number 6055.5, *Industrial Hygiene and Occupational Health*. DoDI 6055.5 directed DoD industrial hygienists to perform comprehensive health hazard evaluations in each workplace in which physical, chemical, or biological hazards may cause illness or death(DoD, 1989). The purpose of the health surveys is:

> to assign priorities for abatement actions, to schedule future surveys, to require personal protective equipment, and to provide a basis for

> determining the requirement and scope of periodic medical surveillance of workers. (DoD, 1989)

While scheduling future surveys, assigning personal protective equipment (PPE), and defining periodic medical surveillance is being accomplished, hazard abatement, at least in abating hazardous noise, has fallen short of required expectations.

The noise abatement shortfall is most noticeable in the rapidly increasing cost of NIHL claims within DoD. Hearing loss claims remained relatively consistent until the beginning of the twenty-first century. However, at the turn of the century, the cost of claims has been rising dramatically each year, with the Department of Veterans' Affairs (VA) paying out an all time high of over 900 million dollars in 2006. In total, the VA has paid over three billion dollars in hearing loss claims since 1977 (CHPPM, 2006).

As with the overall DoD claims, the Department of the Air Force (AF) has also seen rising NIHL cases since 2002. Within the AF, major hearing loss disability cases averaged 161±85 new cases per year from 1996 through 2001. In 2002, the number of new cases increased dramatically to 797 new cases. The average number of new cases between 2002 and 2006 significantly increased ($p<0.05$, t-test) to 952±127 as compared to the 1996-2001 group (Fig 2) (Sweeney & Slagley, 2008). In 2006, the total number of AF veterans receiving compensation for NIHL reached 13,542.

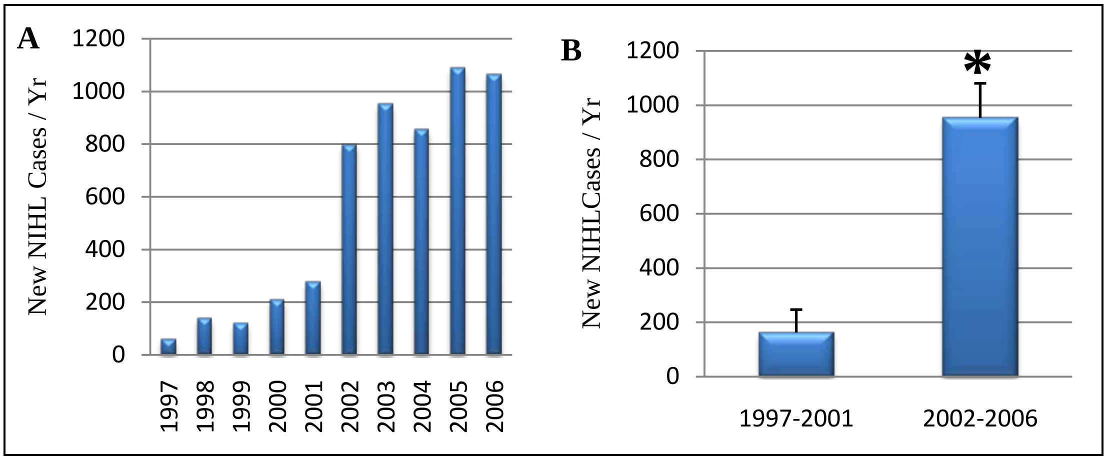


Figure 2: The number of new major hearing loss claims from Air Force veterans. A: New cases per year. B: Mean increase ± SD of new cases per year. *=significant difference ($p<0.05$, t-test)

The increase in NIHL seen in the Air Force may be linked to the high reliance on personal hearing protection devices (HPDs) as the primary control rather than engineering controls. The problem with relying on HPDs is the misuse or complete lack of use of HPDs within the work force. The noise reduction rating (NRR) of the HPD is rated by the manufacturer. However, the manufacturer's NRR often greatly overestimates the effectiveness of the HPD. As shown in Figure 3A, the National Institute for Occupational Safety and Health (NIOSH) performed a study on seven different HPDs that demonstrated HPDs used by untrained workers were as low as 3.8 percent of the reported NRR, with the best HPD being only 71 percent of the manufacturer's rating. Even if the NRRs were adequate to reduce noise levels to an acceptable limit, the HPDs need to be worn consistently to be effective. NIOSH also investigated average use of HPDs among hearing conservation personnel, carpenter safety trainers, and carpenters showing considerably low percentage of use of HPDs (Fig 3B). Finally, Figure 3C shows how even just short unprotected exposure duration can

greatly affect the amount of noise attenuation realized by the worker (Stephenson & Stephenson, 2000).

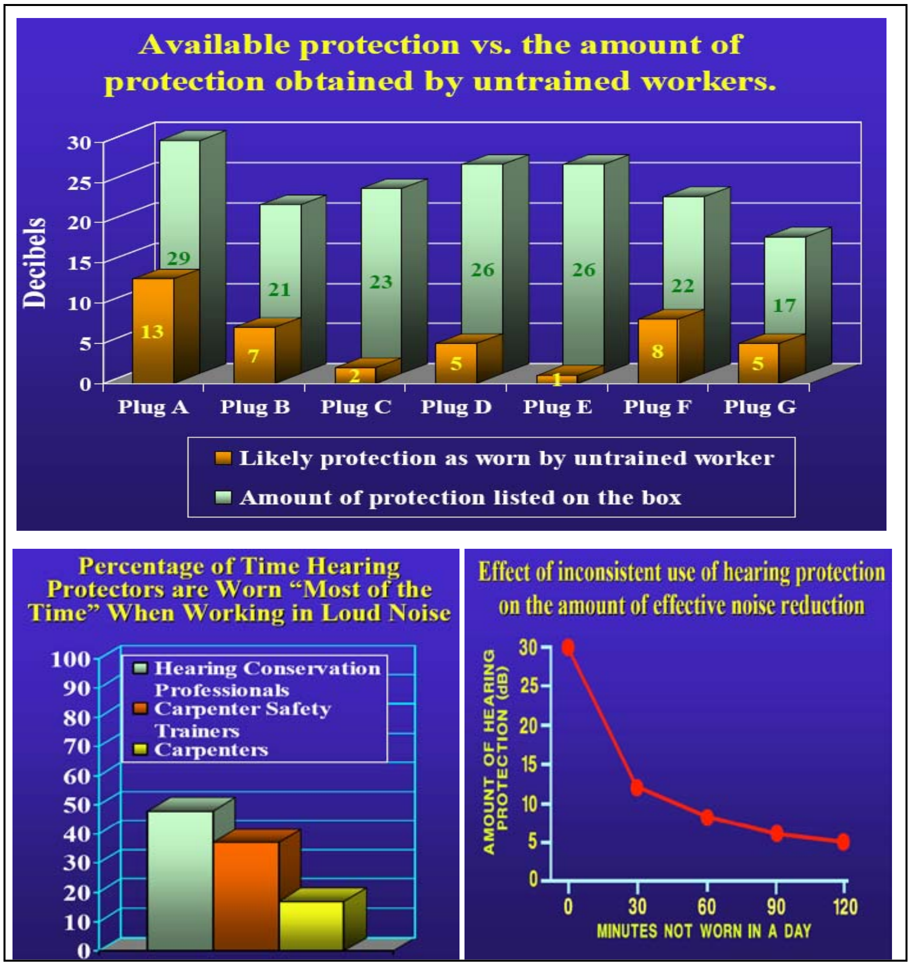


Figure 3: Misuse of HPDs can drastically reduce effectiveness A: Untrained workers have much lower attenuation than reported by the manufacturer. B: Lack of use of HPDs. C: Short durations without HPDs greatly reduce protection**(Stephenson & Stephenson, 2000)**.

Because of the ineffectiveness of HPDs, the high cost associated with hearing loss claims and the permanent deleterious impact on human health, effective hazardous noise control should be a high priority for the Air Force occupational health program. The Air Force mandates that engineering controls shall be the primary method of controlling noise exposure (USAF, 2006). The class of engineering controls known as barriers and

enclosures may be a cost effective means to retrofit existing noise producing equipment, thereby reducing the noise exposure to Air Force personnel.

Dust

As with noise, hazardous workplace atmospheres can contribute to negative health effects. An industrial setting has many potential sources for airborne contamination. Some common sources capable of creating a hazardous atmosphere include chemical vapors, fumes, and particulates. One category of particulates is dust. The airborne hazards can enter the body through three primary routes: inhalation, ingestion, and dermal absorption. Of these three routes, inhalation exposure is the primary concern for particulates (Schaper & Bisesi, 2003). . Some of the common health conditions associated with workplace airborne exposures in U.S. industry include: allergic rhinitis, work related asthma, chronic bronchitis, byssinosis, bronchiolitis, bronchiolitis obliterans, coal worker's pneumoconiosis, silicosis, asbestosis, hypersensitivity pneumonitis, and other fibrosing processes (NIOSH, 2008a).

Engineering control measures should again be the primary focus of controlling hazardous atmospheres. Similar to HPDs, there are many reasons why PPE for hazardous atmospheres, personal respirators, are not always an effective control measure. In fact in a NIOSH survey, 90 percent of workers with required respirator use had at least one indicator of an inadequate respiratory protection program with over 50 percent having 5 or more indicators (NIOSH, 2005). Additionally, between Oct 2006 and Sep 2007, the fifth highest out of 400 OSHA citation types was for respiratory protection violations, issuing a total of 4101 citations (OSHA, 2007).

Within the USAF, many industrial processes expose workers to hazardous chemicals. Although more widespread use of engineering controls have been implemented for airborne hazards as compared to noise hazards, many operations still require respiratory protection. For example, a recent compilation of data showed three out of the four AF beadblast operations sampled were over exposed to hexavalent chromium. Additionally, 29 percent of the bases sampled for painting or priming operations were overexposed to hexavalent chromium (Sweeney, Schmidtgoessling, & Batten, 2008).

Problem Statement

In practical experience, engineering controls for noise and dust are often disregarded due to the complexity of implementing the control. Engineering controls are perceived as requiring complex studies of the problem combined with a detailed analysis of the control. The engineering control is seen as time consuming and expensive. Due to this perception of the difficulty of engineering controls, base level Bioenvironmental Engineers (BEE) more often default to the less effective control of personal protective equipment (PPE) as a substitute for engineering controls. The primary problem this thesis aims to address is to model and develop a simple engineering control that may effectively control hazardous noise and dust in an assortment of USAF applications, thereby enabling base level BEEs to identify when a simple barrier might be an effective engineering control.

Research Focus

Compared to the Air Force, the United States coal mining industry experiences an even greater difficulty in controlling hazardous noise exposures, where 90 percent of coal miners experience hearing impairment(Bauer, Spencer, Smith, & Hudak, 2007). In fact, because of the historical difficulties associated with controlling hazardous noise and hazardous dust levels within the mining industry, NIOSH has identified its top two strategic goals for the mining industry as reducing respiratory diseases and noise induced hearing loss (NIOSH, 2008b). The NIOSH strategic goals were developed in part because research has shown that approximately 20 percent of the coal mine longwall shearer operators exceed regulatory dust levels (Rider & Colint, 2001) and operators are routinely exposed to hazardous noise levels at 151 percent of the allowable daily dose(Joy & Middendorf, 2007). Table 1 summarizes the hypotheses that will be tested.

Table 1: Outline of hypotheses tested

Test Performed	Null Hypothesis (H_o)	Alternative Hypothesis (H_A)	Statistical Method
Pilot study	A rubber partial barrier placed between an operator and the cutting drum of a Longwall shearer will not reduce the noise to the operator	A rubber partial barrier placed between operator and cutting drum will reduce the noise to the operator by more than 3 dB(A)	Compare means (n=3)
Reproduce underground shearer noise in a sound studio	Sound studio equipment cannot reproduce a similar frequency spectrum from a recording of an underground shearer operation as compared to actual underground noise	Sound studio equipment can reproduce a similar frequency spectrum	Compare frequency spectrums
Partial barrier test in a sound studio	The recorded shearer noise cannot be reduced by at least 3 dB(A) from a partial barrier in a semi-reflective environment	The recorded shearer noise can be reduced by at least 3 dB(A) from a partial barrier in a semi-reflective environment	t-test on means (n=3)

Test Performed	Null Hypothesis (H_o)	Alternative Hypothesis (H_A)	Statistical Method
Sound intensity measurement of recorded noise	The sound intensity of the audio equipment was measured to use in calculations. Hypothesis is that this is a not a valid measurement	Sound Intensity is a valid measurement	Compared to previously published methods
Room absorption coefficient	The measured room total absorption (TA) will not equal the calculated TA	The measured room TA will equal the calculated TA	± 10%
Calculation of noise reduction from the barrier	The calculated noise reduction using standard equations for sound calculations will not equal the measured noise reduction	The calculated noise reduction using standard equations for sound calculations will equal the measured noise reduction	± 10%
Partial and Full barrier tests in a simulated Longwall test facility	A partial or a full barrier will not significantly reduce the sound level at the operator position	A partial or a full barrier will significantly reduce the sound level at the operator position	ANOVA
Dust testing in a simulated Longwall test facility	A partial or a full barrier will not reduce the dust level at the operator position below regulatory standards	A partial or a full barrier will reduce the dust level at the operator position below regulatory standards	ANOVA
Room absorption coefficient at the Longwall test facility	The measured room TA will not equal previously published date TA for an underground mine	The measured room TA will equal previously published date TA for an underground mine	± 10%

Methodology

The purpose of the current project is to model and build a barrier to mount on a simulated longwall coal mine shearer between the shearer operator and the cutting drum to passively control hazardous noise and dust levels. The measured outcome will be compared to theoretical values to validate insertion loss (IL) for partial barriers in a semi-reverberant field. If the barrier is shown to be a cost effective method of reducing noise and dust exposure under the simulated mining operations, it may also have applications within the Air Force to help reduce noise and dust exposure.

Assumptions/Limitations

The work of this thesis is intended to provide a conceptual basis for designing and building simple engineering controls for occupational exposure to hazardous noise and dust. The work is not intended to be the final design for application in a coal mine longwall operation. Nor is this thesis intended to be a measure to control all noise and dust issues within the USAF. It is assumed, rather, that the thesis can be used as a beginning point when base level BEEs identify a noise or dust source that may be able to be controlled with a barrier.

2. Literature Review

Noise

Within the hierarchy of controls, engineering, administrative, and PPE, hazardous noise is perhaps the most ill-suited for PPE as compared to the many other hazards found in industrial work centers. For example, an uncontrolled painting operation may be irritable enough to the worker to induce the continuous use of a respirator. Likewise, the dust generated from a sanding operation is a visible hazard, again confirming to the worker a respirator is a valuable control. Similarly, industrial radiation hazards are feared by many workers, where the workers strictly adhere to administrative and PPE controls. However, with hazardous noise, workers have many perceived reasons, whether legitimate concerns or cultural norms, for not wearing PPE to protect against hearing loss.

In a study investigating the personal and social aspects of HPD use within Appalachia coal miners, the investigators interviewed 31 miners from four different

mines to determine the reasons why HPDs are not routinely utilized in hazardous noise environments. The results ranged from miners reporting it was already too late; they were already deaf, to increased ear infections from using dirty plugs, to reduced safety due to not being able to hear the "roof talk" which is the subtle changes in cracking and shattering of the mine's ceiling (Murray-Johnson, et al., 2004; Patel, Witte, Zuckerman, & Murray-Johnson, 2001). Coal miners claim they can hear the type of sound that may indicate an imminent collapse of the mine (Holmes Safety Association, 1999). Thus, a better means of controlling hazardous noise exposure may be engineering controls or engineering controls in combination with PPE.

In 1999, the Mine Safety and Health Administration (MSHA) developed a comprehensive noise control guide for underground mining (MSHA, 1999). For longwall mining, the recommended control for new equipment purchases is remote control, which would isolate the operator from the source. For existing equipment, a number of controls are recommended as listed below:

1. Locate the pump station in the intake entry, out by the headgate, away from where miners normally perform their duties.
2. Fully enclose the stageloader (except for the entrances and exits) with secure, sealed, rigid covers.
3. Attenuate the stageloader scrubbers as much as possible. Direct scrubber discharge away from operator locations.
4. Install sound-absorptive material on motors, panels, and gearboxes provided that overheating does not occur.
5. Design the entrance doors or chain curtains on the crusher to minimize the number of loose parts that can rattle. If possible, replace the chain curtains with conveyor belting.
6. Cover the end of the stage loader discharge with conveyor belting.
7. Attach belting to the shearer spray arms in a manner so that the belting extends above the spray arms. (MSHA, 1999)

None of the recommended controls, however, suggest using a sound barrier to isolate the worker from the noise. This may be due to the thought that the coal mine was too reverberant for a barrier to be effective; however, a recent study performed by NIOSH showed the coal mine may be more absorptive than previously conceived (Kovalchik, Matetic, Cole, & Smith, 2007).

As with the mining industry, the use of HPDs for Department of Defense personnel may not be an effective means of controlling hazardous noise exposure. As mentioned with the mining industry, the need for personal accountability directly affects the amount of protection the HPDs provide. Combining the personal reliance factor with the low effectiveness of HPDs as shown earlier in figure 3, HPDs do not seem a likely choice of protection from hazardous noise.

CHPPM has attempted to address at least one of the complaints of HPDs, the ability to hear necessary sound, while blocking the hazardous noise.   CHPPM has experimented with two types of HPDs that would be better suited to the field soldier. First, an active control system that uses microphones and plugs to enhance low noise, while at the same time reduce high noise(CHPPM, 2004a). A second method is a modified plug with a disjointed channel, allowing for effective communication yet remaining effective at blocking high sound levels (CHPPM, 2004b). While these devices may address one complaint of HPDs and improve the use of HPDs, it still does not address the personal reliance of the user to always effectively wear the HPD in a hazardous noise environment.

Because of the ineffectiveness of HPDs, engineering noise controls should be the permanent solution to controlling occupational exposure to hazardous noise. One

effective engineering control in a direct noise field is a partial barrier (Driscoll & Royster, 2003; Bruce, Bommer, & Moritz, 2003). With this application, the receiver of the noise must be blocked form the direct line of sight of the sound source, or be in the "sound shadow" (Driscoll & Royster, 2003). While full and partial enclosures have been tested in above ground mining, no published data was found to show a barrier being tested underground. This may be due to underground mining generally being thought of as a very reverberant field (Yantek, Jurovcik, & Ingram, 2007), in which a partial barrier would not be effective.

Dust

As mentioned previously in this document, PPE for dust may not be an effective means of controlling exposures where a NIOSH survey suggested 90 percent of workers with required respirator use had at least one indicator of an inadequate respiratory protection program (NIOSH, 2005). Although the study was not limited to mining, there is no indication miners use respirators more effectively than the general industrial population.

In a second study, the investigators provided coal miners with personal direct read dust monitors to provide instant feedback on dust exposures. Prior to this study, many miners would only be aware of high dust levels from indicators such as chest x-rays, doctor's warnings, or physical signs such as coughing or shortness of breath. Thirty miners were trained on the use of the personal monitoring devices. Twenty-seven of the thirty miners reported noticing fluctuations in dust levels. Of these, seventeen were surprised by the high levels, suggesting the miners are not aware of when they are being exposed. Some of the miners noticing fluctuations in the dust

levels attempted to change the work environment. Fifteen changed position, three changed ventilation, four changed position and ventilation, but only one wore his respirator. The study has two critical findings. First, miners may not be aware of when they are being overexposed to hazardous dust, and second, even when aware of the overexposure, miners are reluctant to wear their respirators (Peters, Vaught, Hall, & Volkwein, 2007).

Engineering dust controls have been widely implemented within the coal mine industry. However, most of these controls have high implementation costs, high operating costs, and do not always reduce the dust levels below the acceptable standards. For example, forced ventilation in combination with air sprayers is often utilized in coal mine long wall operations to control dust levels. The average minimum ventilation headgate velocity throughout U.S. coal mines was reported as 24.5 m^3/sec (n=44), which is a 65 percent increase over mid-1990 levels (Rider & Colinet, 2006). The number of spray nozzles used in longwall mining ranged from 30 to 62, with an average spray pressure of 551 kPa. The mines reported 75-90 percent of the nozzles must be operational when mining. In spite of the increased ventilation and use of spray nozzles, the study showed many workers are still over the regulatory limits (Rider & Colinet, 2006). An additional engineering control of a shield to separate the miner from the source of the dust, the cutting drum, may reduce dust levels, while at the same time allow for decreased use of water spray nozzles, thereby decreasing operating expenses. A previous study utilizing a full mesh partition indicated a reduction in dust could be achieved by separating the source from the

operator. However, in that study, the full mesh partition blocked the view of the cutting drum and therefore did not have miner acceptance (Bureau of Mines, 1994).

3. Methods

Pilot Study

Initial field tests were conducted in an underground coal mine longwall shearer operation. A 178x86x0.635 cm (70x34x0.25 in) rubber sheet was used as a partial sound barrier. The sheet was held between the shearer operator and the cutting drum to reflect the direct noise path. Sound measurements were taken at the shearer operator's head position. The measurements were repeated three times each with the sheet up then removed to get an average noise reduction of 3.8±0.8 dB(A) at the operator's position. Readings were repeated with the sheet up then removed several times to get an average IL of 3.8 ± 0.8 dB(A) (Slagley & Sweeney, 2007).

Tests Performed at Wright Patterson Air Force Base (WPAFB)

Sound Reproduction at the WPAFB Test Facility

The initial underground tests warranted further investigation into engineering noise controls for the longwall shearer. Therefore, an above ground model of the underground noise was developed and tested to determine if similar sound levels and frequency responses could be created. A 24x4x2.4 m semi-reverberant room was used to test if shearer noise could be reproduced above ground in order to further develop the partial sound barrier. The room was comprised of tile flooring, suspended acoustical tile ceiling, and sound absorption tiling with several layers of paint fixed to all of the walls. Recorded noise from an actual shearer operation was provided by MSHA. This recording

was played back through a Dell® laptop computer (Dell®; Round Rock, Texas) connected to a Bogen® Gold Seal Series GS^3 250 pre-amplifier (Bogen® Communications; Ramsey, New Jersey). The pre-amplifier was routed through a dbx 223XL crossover (dbx Professional Products; Sandy, Utah) which was connected to two QSC® RMX-1450 amplifiers (QSC Audio; Costa Mesa, California). The first amplifier was connected to two Peavey® 115 loudspeakers (Peavey Electronics Corporation; Meridian, Mississippi) for middle and high frequency output. The second amplifier was connected to two Peavey® 118 subwoofers for low frequency output. Each set of speakers was connected in series with a second loudspeaker or subwoofer. Twelve gauge Livewire® speaker cable with a length of 15.25 meters connected the amplifier to the first set of speakers followed by a 15.25 meter long 14 gauge Livewire® speaker cable from the first speaker to the next (Appendix A) (Sweeney & Slagley, 2008).

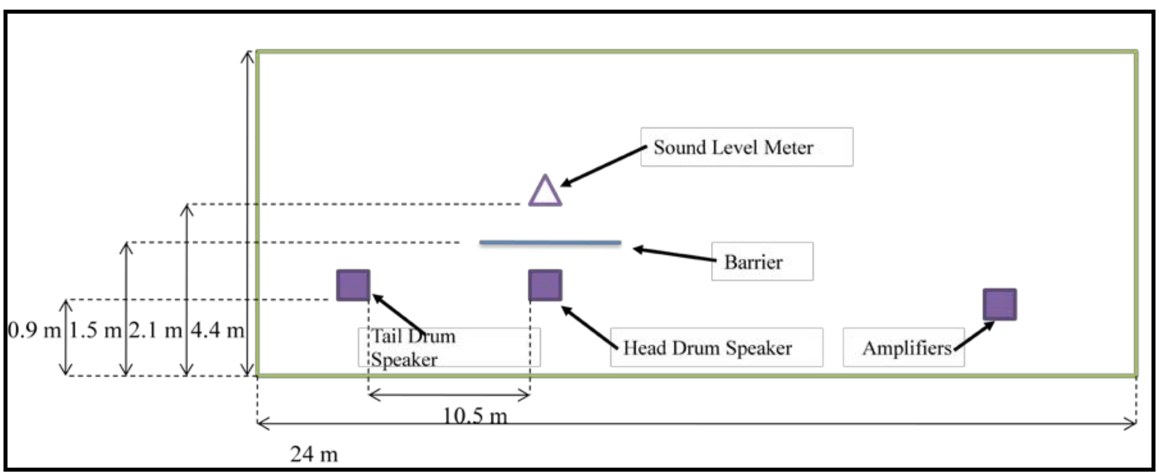


Figure 4: Audio equipment configuration at WPAFB test facility

The audio equipment allowed for both sound output control and frequency adjustment, enabling the operator to match the frequency spectrum of the actual

underground recordings. The settings of each component of the audio equipment are at Appendix A.

A partial barrier was constructed of a 2.4 m long, by 1.8 m high, by 1.3 cm thick piece of plywood. The barrier was placed half-way between the speakers and the simulated position of the shearer operator and moved from one speaker location to the next (Fig 5). Plywood was chosen for the barrier because of its availability and it should have similar acoustical properties of the final barrier tested, which was clear acrylic. In a single barrier configuration, thicker material can have a higher transmission loss (Uris, Llopis, & Llinares, 2001). Therefore, because the plywood was thicker than the acrylic used later, the plywood may reduce the noise to the operator to a greater extent. However, the intent of the experiments performed at WPAFB was to demonstrate feasibility prior to testing the full scale model.

Partial Barrier Test at the WPAFB Test Facility

The noise was recorded using a Larson Davis Model 831 octave band analyzer (OBA) (Larson Davis, Provo, Utah). The OBA was mounted to a tripod 1.5 m above the ground. Three measurements were taken with and without the barrier in place at each speaker location. The measurements were taken as a 20 second average sound pressure level and reported as either 1/1 octave band, 1/3 octave band, or A-weighted decibels (dB(A)). The meter was placed directly across from the speaker at a distance of 1.2 m (Fig 5).

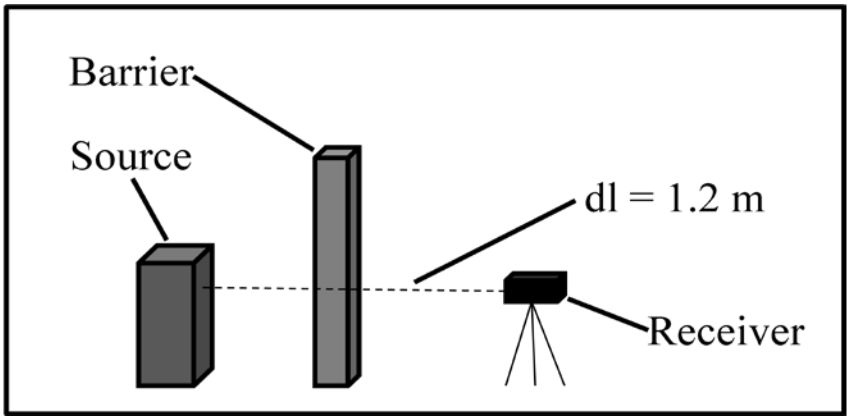


Figure 5: Placement of OBA from source

Sound Intensity Measurement

Sound intensity level was measured for each speaker set in order to calculate sound power level. All audio equipment was configured as mentioned in the previous section. The sound intensity was measured with a Norsonic sound intensity probe type 216 connected to a type 830 real time analyzer (Norsonic AS, Tranby I Lier, Norway). The box method was used for the sound intensity measurements with a 17.2 meter rectangular "box" surrounding the speaker set. All sound intensity measurements were taken 0.6 meter from the corresponding speaker surface (Sweeney & Slagley, 2008). To create the "box" around each speaker, 13 measurements were taken surrounding the speakers, 4 at the front and 4 at the back, 2 at each side, and 1 at the top (Fig 6). Each measurement was taken as a 20 second average. Measurements for each 1/1 octave band, dB(A), dB(C), and dB line were entered into a Microsoft Excel® spreadsheet.

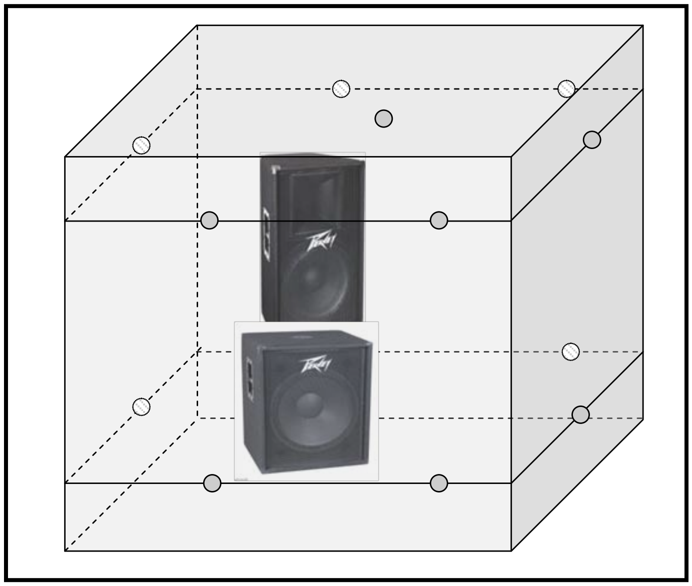


Figure 6: Sound intensity probe locations

Room Absorption Coefficient

An electronic buzzer with a measured sound power level was used as a noise source and placed in the center of the room. A grid was measured for the room with full octave sound intensity level measurements taken at three locations across the width of the room and nine locations across the length of the room, for a total of 27 measurements. The measurements were used in equation (1) in the calculations section of this document to determine the average room's total absorption (TA) coefficient for each octave. Additionally, the TA was estimated for the room using published absorption coefficients for each room material for comparison purposes.

The buzzer's sound power was estimated in a free field using the Larson Davis OBA. In contrast to the sound power measurements with the speakers, a spherical model was used to estimate the sound power rather than the box model. A 3 m (10 ft) string was

attached to the base of the sound meter and to the buzzer to create a consistent radius which calculates to a surface area of 117 m^2 (1256 ft^2).

Calculation of Noise Reduction from a Partial Barrier

The overall expected values for the sound pressure level within the WPAFB test facility was calculated by logarithmically adding each contributing sound source. In this study, the contributing sources were the sound from the un-attenuated speaker, the sound diffracted over the barrier from the attenuated speaker, and the reflected sound off the ceiling from the attenuated speaker.

All calculations were performed for each full octave separately between 31.5 and 8000 Hz. The first calculation for the un-attenuated speaker used the equation for calculating sound levels in a reverberant space (equation 1) (Bruce, Bommer, & Moritz, 2003).

$$L_p = L_w + 10 * \log_{10}\left(\frac{Q}{4\pi r^2} + \frac{4}{TA}\right) \tag{1}$$

Where L_p is the sound pressure level, L_w is the sound power level of the source, Q is the directivity factor of the source, r is the distance from the source to the receiver, and TA is the room absorption factor. Sound power (L_w) was calculated from the average intensity (L_i) over the total area of the box using equation (2).

$$L_w = L_i + 10 * \mathrm{Log}_{10}(\text{Area of the box around the speaker}) \tag{2}$$

L_i was calculated as the average intensity level using the logarithmic average of the 13 measured points around the "box" surrounding the speaker using equation (3). The "box" surface area was measured as 17.22 m^2.

$$L_i = 10 * \log_{10}\left(\frac{1}{n} * \sum_1^n 10^{\frac{L_{i_n}}{10}}\right) \quad (3)$$

The directivity factor used was 2 for reflection off the floor only.

The noise reduction from the diffracted source was determined from the path difference over the barrier versus the direct path from the source (Fig 7).

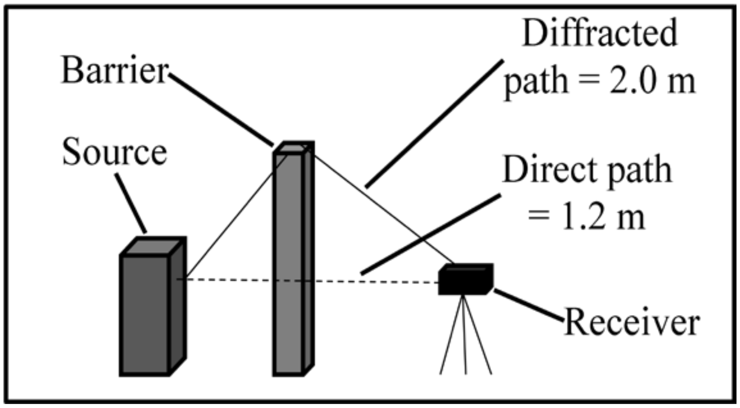


Figure 7: Diffracted sound path over barrier

After calculating the path difference, the insertion loss value was obtained from table 21.11 of *The Occupational Environment* (Bruce, Bommer, & Moritz, 2003).

The third noise source, the noise reflected from the ceiling, was calculated using equation (4), where IL_c is the difference between the level of the direct sound without the barrier and the sound level reflected off the ceiling, d_c is the path length the sound travels to the ceiling and down to the receiver, d_l is the direct path length from source to receiver, and α is the absorption coefficient of the ceiling (Fig 8).

$$IL_c = 10 * \mathrm{Log}_{10}\left[\left(\frac{dc}{dl}\right)^2 * \frac{1}{1-\alpha}\right] \quad (4)$$

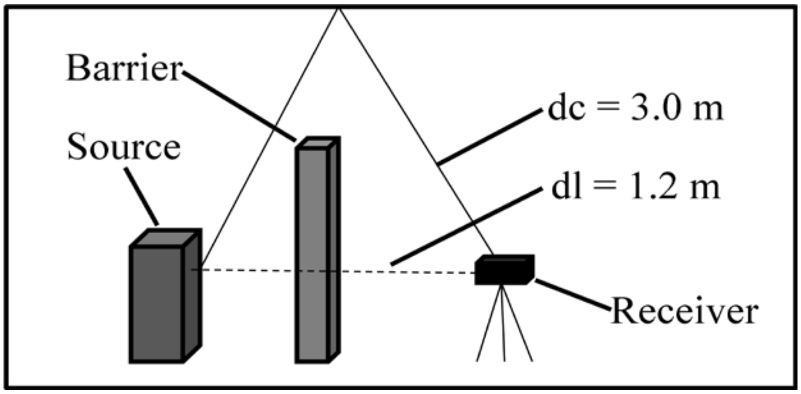


Figure 8: Ceiling noise reflection path

Finally, all three noise sources were logarithmically added for a total estimated sound level at the receiver position using equation (5).

$$\text{Total L} = 10 * \log_{10}\left(\sum_{1}^{n} 10^{\frac{L_n}{10}}\right) \tag{5}$$

After the predicted noise level with the barrier in place was calculated, the value was subtracted from the measured noise level without the barrier in place for each location to determine the estimated insertion loss value for the barrier, which could then be compared to the measured insertion loss.

Testing at the NIOSH-PRL Facility

Barrier Construction

The full scale model of the longwall shearer at the NIOSH-PRL facility was built primarily of plywood sheeting and a wooden support frame to match the approximate configuration of an actual underground shearer. The model has two steel cutting drums that rest on the simulated coal face, which is plywood over corrugated steel. The walkway is a narrow path similar to the area an operator would be working in underground. The shields above the walkway are plywood and steel and represent a moving support structure that would protect the operator from the ceiling caving in.

Behind the walkway and shields is an open space of approximately 2 m (6 ft) that is used to represent the "gop" area of the underground operation (Fig 9A). In longwall mining, the shearer cuts along the coal face, progressing forward into the face. The shields keep the mine ceiling from collapsing in on the worker. As the shearer moves, the shields move with it, allowing the mine ceiling to collapse behind the workers. This area is the gop space comprised of loosely packed rock and earth.

Three partial barrier configurations and a full barrier were built and mounted on the shearer to test the effectiveness of each barrier for noise and dust level reductions at the typical operators' position. A potential concern of a barrier mounted to the longwall shearer is the operators' visibility of the cutting drum. To address this issue, clear acrylic sheeting was used, as well as several barrier configurations to balance visibility and practicality with noise reduction. A thicker, sturdier barrier would be required in an actual underground operation, which may further increase noise reduction. The greater the amount of barrier surface area, the greater the sound shadow will be, which should correspond to a greater sound reduction to the operator. Because the shearer is mobile, the underground barrier would either have to have a gap between the top of the barrier and the ceiling, or have a flexible portion near the top to allow for the changing ceiling height. The dimensions of the barrier were chosen for practicality in this experiment. It may be necessary to change the dimension for underground operations. However, as long as the operator remains in the sound shadow, the barrier should effectively reduce the noise levels.

The partial barrier was constructed of 1.22 by 0.61 m (4 x 2 ft) clear acrylic sheets with a thickness of 0.95 cm (3/8 in). Each sheet was mounted in series to a wooden

frame that extended the full length of the shearer just beyond each cutting drum. The partial barrier left approximately a 0.6 m (2 ft) gap between the top of the barrier and the shield (Fig 9B).

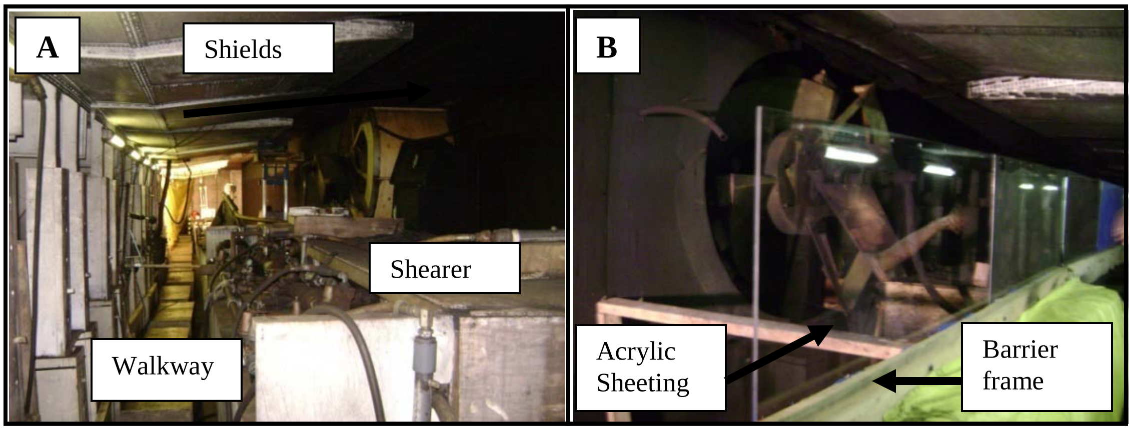


Figure 9: Mock longwall shearer with: A: No barrier and B: The partial barrier

The full barrier was constructed by attaching rubber sheets to the top of the partial barrier to create a flexible seal that could adjust with the shield height as shown in figure 10. The blue portion shown in the figure was a protective coating on the acrylic sheets that was later removed. The four barrier configurations tested are shown in figure 11 below.

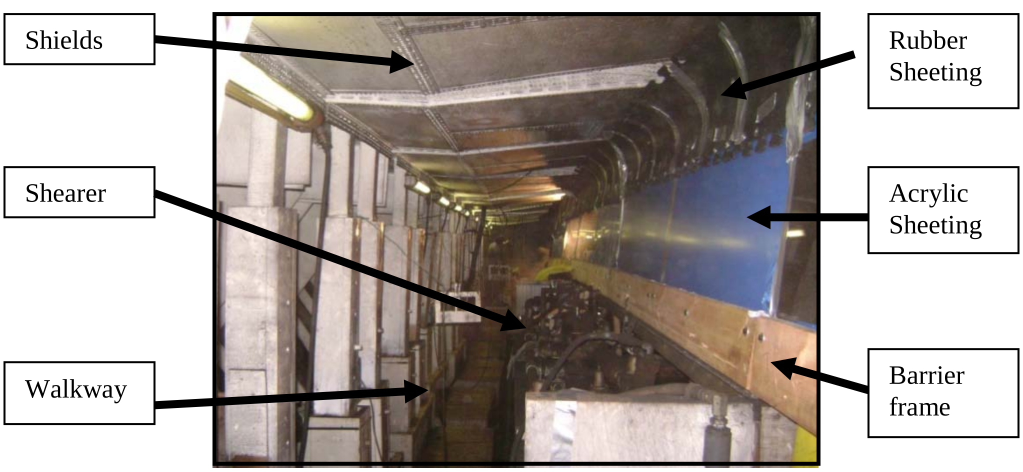


Figure 10: Barrier mounted on mock-shearer

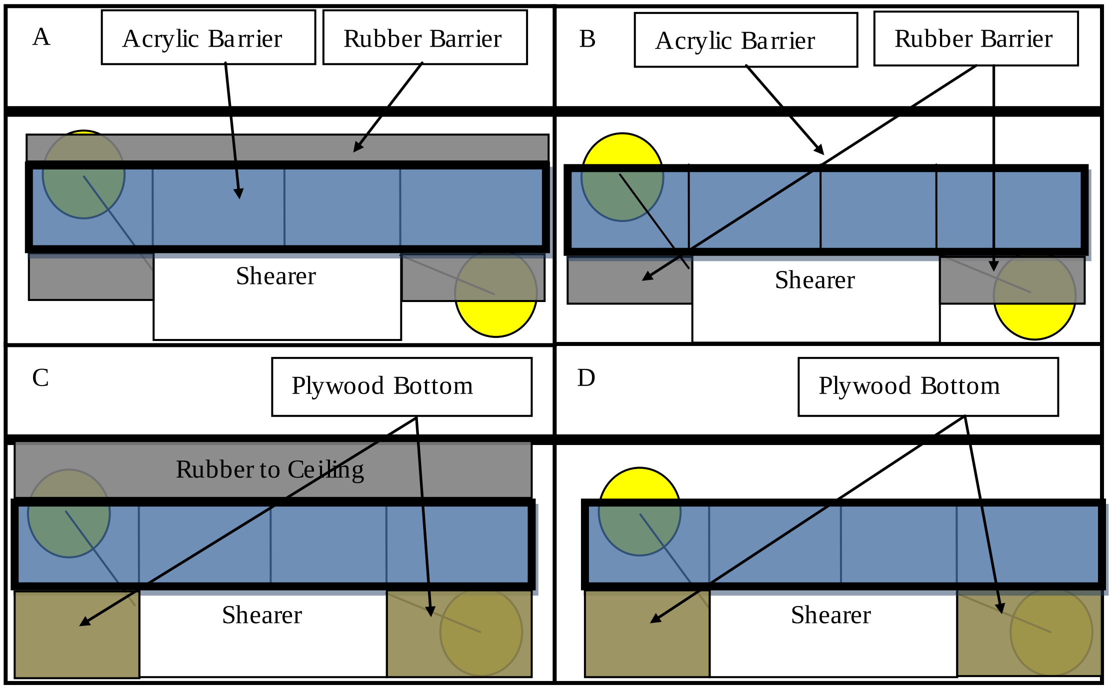


Figure 11: Four barrier configurations tested for noise reduction

Sound Testing

The same audio set-up was utilized at the NIOSH-PRL longwall test facility. Three days of noise testing was performed. The first two days were spent testing the best configuration and speaker placement, along with constructing the barrier (Fig 12).

Figure 12: A: Speaker location at headgate drum and B: Sound meter on tripod

Some of the methods tried but not used included facing the speakers towards the simulated face to increase the sound scattering. This did not provide adequate sound levels nor correct frequency response. The third day recorded sound measurements in five configurations: no barrier, a partial barrier with a partial rubber bottom, a partial barrier with a partial rubber bottom and top extending to the ceiling, a partial barrier with a full wooden bottom section, and a full barrier from floor to ceiling (Fig 13).

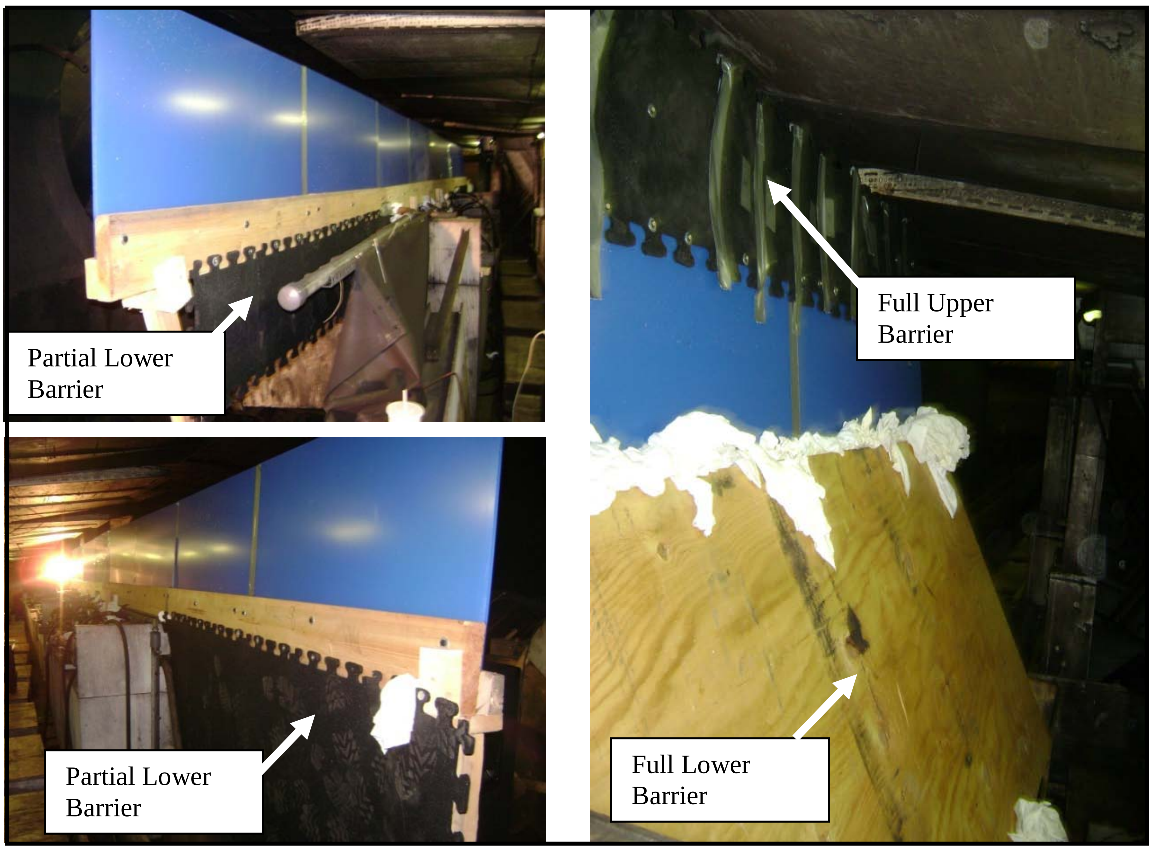


Figure 13: Partial and full noise barriers

Three positions were tested, at the headgate drum, the center of the machine, and the tailgate drum for each barrier configuration (Fig 14, vertical solid arrows). At each test location, three heights were tested, 132 cm (52 in) from the floor to simulate the ear height of the fifth percentile female, 162.5 cm (64 in) for the 50th percentile male and

172.5 cm (68 in) for the 95th percentile male (Annis & McConville, 1996). Additionally, each location and height was tested for noise reduction using a pink noise generator to determine if changing the frequency spectrum would have a large influence on the amount of attenuation from the barrier.

The TA was measured for the longwall test facility using a similar technique as performed in underground coal mine absorption coefficient tests (Kovalchik, Matetic, Cole, & Smith, 2007). The sound source was placed in two locations to measure the TA. The buzzer was first placed in the middle of the walkway centered between shield supports 11 and 12 and suspended from the ceiling 1.83 m (72 in) above the floor (0.66 m (26 in) below the ceiling). Sound level was measured at ten locations along the center of the walkway at a height of 1.55 m (61 in) above the floor. The buzzer was then moved to the simulated face, again centered between shields 11 and 12 and 0.91 m (36 in) above the shearer (0.66 m (26 in) below the ceiling). The sound level was measured at five locations along the center of the walkway. All measurements were taken as 30 second averages (n=2 at each location).

Dust Testing

To measure the effectiveness of the full (acrylic sheets plus rubber to ceiling) and partial barrier (acrylic sheets only), tests were performed in an above ground full scale mock-up of a coal mine longwall operation following previously published procedures. Briefly:

> Tests to evaluate the [effects that a partial and full barrier] have on dust levels on the longwall face [were] conducted at a full scale longwall test facility at the National Institute for Occupational Safety and Health Pittsburgh Research Laboratory (NIOSH-PRL). The simulated face is

> 38.13-m [125-ft] long and the height from floor to roof is 2.29-m [7.5-ft] as shown in Figure [13]. Twenty-four simulated shield supports [1.52-m (5-ft) wide] cover the length of the test facility. A full scale wooden mock-up of a Joy 4LS double ranging arm shearer was located approximately one half of the distance from the headgate to the tailgate. . . Ventilation for the longwall gallery was provided by two exhaust fans capable of supplying approximately 19.17 m^3/sec (40,500 cfm) of air along the face. (Rider & Colint, 2001)

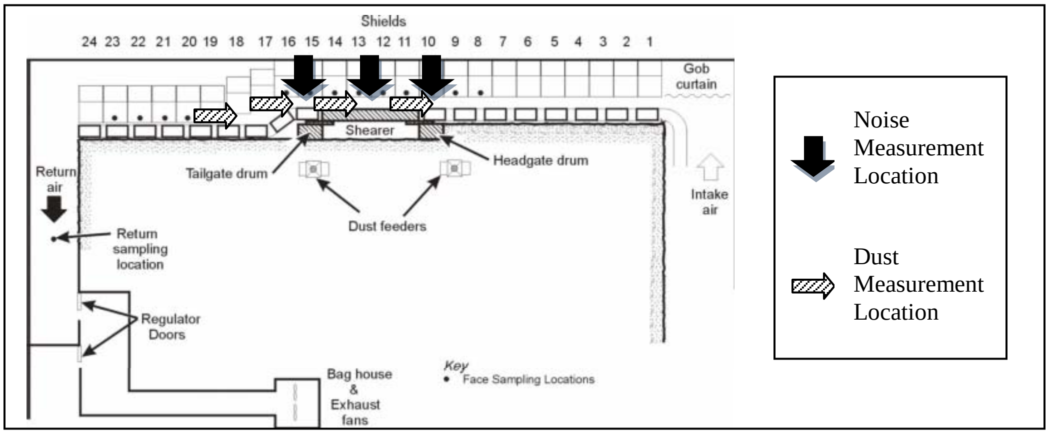


Figure 14: Simulated full scale longwall facility at NIOSH-PRL **(Rider & Colint, 2001)**

Commercially available respirable coal dust was fed into the longwall gallery at the head and tail drum via a screw type feeder into mini educators. Compressed air carried the coal dust from the educators into the gallery to produce dust at the drum locations.

Four real-time aerosol monitors (RAMs) were used to measure dust levels (Fig 15). The RAMs were suspended from the shield supports at breathing zone level near shields 10, 12, 15, and 18 to approximate the shearer operator and the jacksetter positions (Fig 13, horizontal, hashed arrows). The air was pulled through a 10-mm cyclone at 2 L/min to separate and measure the respirable dust. Measurements were averaged and recorded every two seconds.

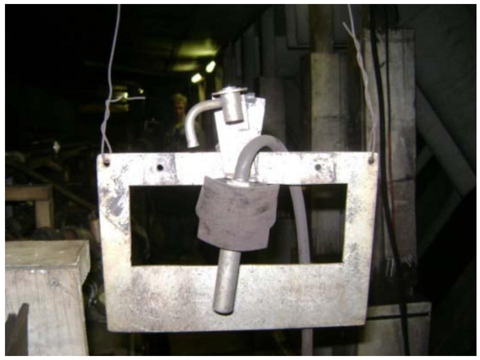


Figure 15: Suspended RAM

Dust tests were conducted at three different ventilation face velocities for each barrier configuration: no barrier, the partial barrier, and the full barrier. Each test was run for approximately 10 minutes. The face velocity remained relatively consistent between configurations for each respective ventilation speed, which was measured upstream of the mock shearer near shield number six with a direct read anemometer. The results are shown in Table 2 for each test configuration (± one standard deviation).

Table 2: Relative face velocities for each configuration

Relative Velocity	No Barrier		Partial Barrier		Full Barrier	
	(m^3/min)	(ft^3/min)	(m^3/min)	(ft^3/min)	(m^3/min)	(ft^3/min)
Low	13.6 ± 1.0	480 ± 35	13.9 ± 0.8	490 ± 30	13.9 ± 0.8	490 ± 30
Medium	19.0 ± 1.1	670 ± 40	19.0 ± 1.0	670 ± 35	19.1 ± 1.0	675 ± 35
High	23.5 ± 1.4	830 ± 50	23.8 ± 1.4	840 ± 50	24.0 ± 1.4	850 ± 50

4. Results

Table 3 outlines the results of each test performed, and when applicable, the statistical results. Appendix C provides the detailed statistical analysis.

Table 3: Outline of hypotheses results

Test Performed	Null Hypothesis (H_o)	Alternative Hypothesis (H_A)	Result
Pilot study	A rubber partial barrier placed between an operator and the cutting drum of a Longwall shearer will not reduce the noise to the operator	A rubber partial barrier placed between operator and cutting drum will reduce the noise to the operator by more than 3 dB(A)	Reject H_o, accept H_a: The rubber barrier reduced noise to the operator by 3.8 ± 0.8 dB(A)
Reproduce underground shearer noise in a sound studio	Sound studio equipment cannot reproduce a similar frequency spectrum from a recording of an underground shearer operation as compared to actual underground noise	Sound studio equipment can reproduce a similar frequency spectrum	Reject H_o, accept H_a: The frequency spectrum was reproducible above ground with audio equipment
Partial barrier test in a sound studio	The recorded shearer noise cannot be reduced by at least 3 dB(A) from a partial barrier in a semi-reflective environment	The recorded shearer noise can be reduced by at least 3 dB(A) from a partial barrier in a semi-reflective environment	Reject H_o, accept H_a: The noise level was reduced by 10.3 dB(A) ($p<0.005$) for the headgate position and 13.2 dB(A) ($p<0.005$) for the tailgate position
Sound intensity measurement of recorded noise	The sound intensity of the audio equipment was measured to use in calculations. Hypothesis is that this is a not a valid measurement	Sound Intensity is a valid measurement	Reject H_o, accept H_a: The established procedures are acceptable
Room absorption coefficient	The measured room total absorption (TA) will not equal the calculated TA	The measured room TA will equal the calculated TA	Fail to reject H_o: The measured TA was not within 10% of the calculated TA
Calculation of noise reduction from the barrier	The calculated noise reduction using standard equations for sound calculations will not equal the measured noise reduction	The calculated noise reduction using standard equations for sound calculations will equal the measured noise reduction	Fail to reject H_o: The measured TA was not within 10% of the calculated TA for both positions
Partial and Full barrier tests in a simulated Longwall test facility	A partial or a full barrier will not significantly reduce the sound level at the operator position	A partial or a full barrier will significantly reduce the sound level at the operator position	Reject H_o, accept H_a: The barrier did significantly reduce the noise to the operator ($Prob > F = 0.0001$)

Test Performed	Null Hypothesis (H_o)	Alternative Hypothesis (H_A)	Result
Dust testing in a simulated Longwall test facility	A partial or a full barrier will not reduce the dust level at the operator position below regulatory standards	A partial or a full barrier will reduce the dust level at the operator position below regulatory standards	Reject H_o, accept H_a: The dust levels were significantly reduced for all positions except the jacksetter (Prob > F = 0.0001)
Room absorption coefficient at the Longwall test facility	The measured room TA will not equal previously published date TA for an underground mine	The measured room TA will equal previously published date TA for an underground mine	Fail to reject H_o, the measured TA at the test facility was not within 10% of the underground coal mine TA

Tests Performed at WPAFB

Sound Reproduction at the WPAFB Test Facility

The MSHA-provided noise recording was successfully generated through the loudspeaker system at the test facility for frequencies above 40 Hz (Fig 16). The noise model readings reported are an average of three readings taken with a Larson Davis OBA. Each measurement is the sound equivalent level over a 20 second period. For the primary frequencies of concern for developing engineering noise controls (125-10,000 Hz) the spectrum was reproduced to within ± 5 decibels at each 1/3 octave band.

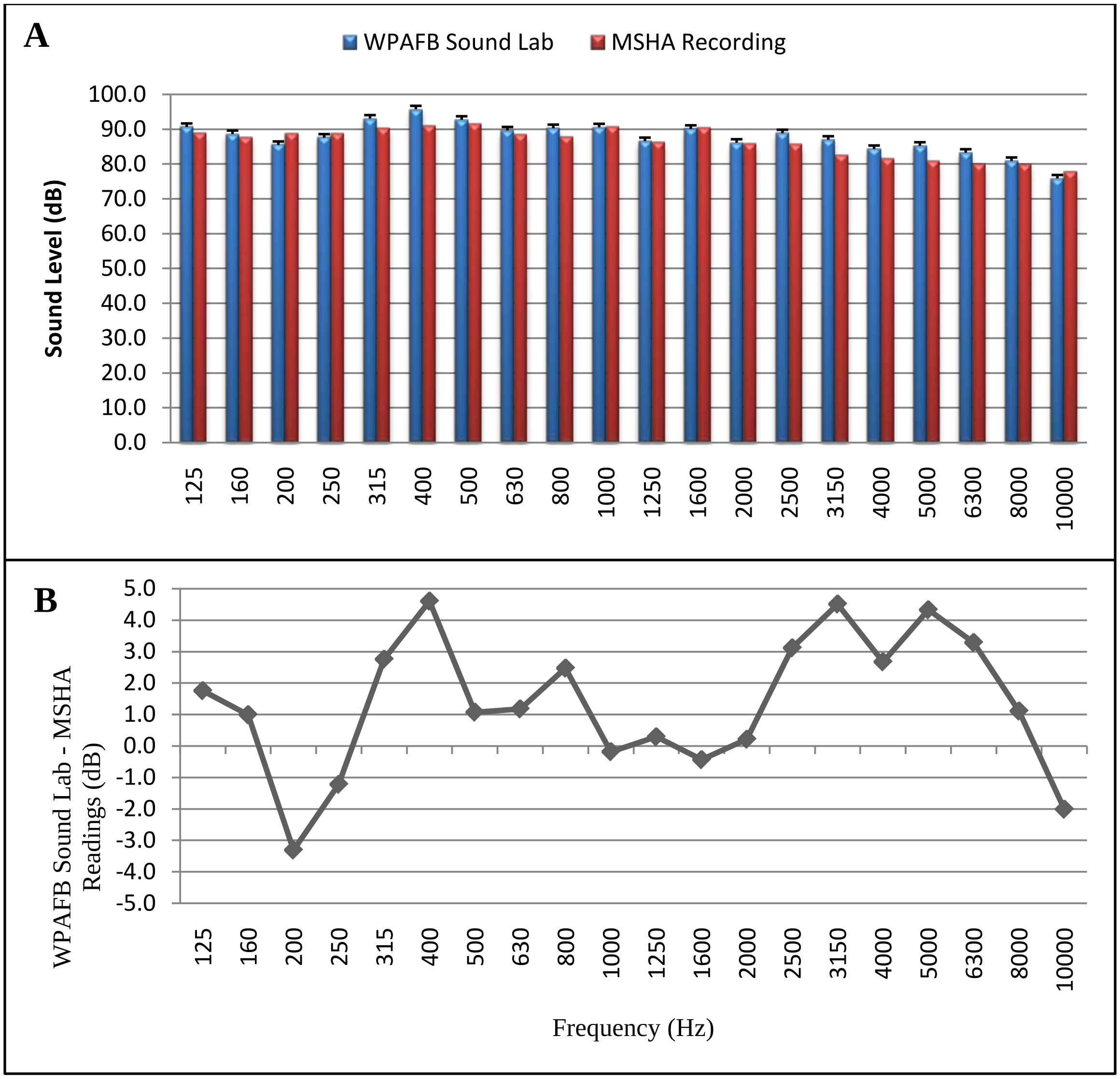


Figure 16: A: Mean frequency response of reproduced shearer noise vs. MSHA recorded spectrum (n=3, error bars ±1 SD). B: Mean difference in frequency response.

Sound Measurement at the WPAFB Test Facility

Sound measurements were recorded at the simulated headgate and tailgate positions with and without the plywood barrier. Three measurements were taken for each variation. The average noise reduction from the barrier was 13.1 ± 0.4 dB(A) and 10.3 ± 0.4 dB(A) for the tailgate drum and headgate drum, respectively. Figure 17 shows the

frequency spectrums with and without the barrier for the headgate drum (A) and tailgate drum (B). The mean sound reduction is shown in figure 18.

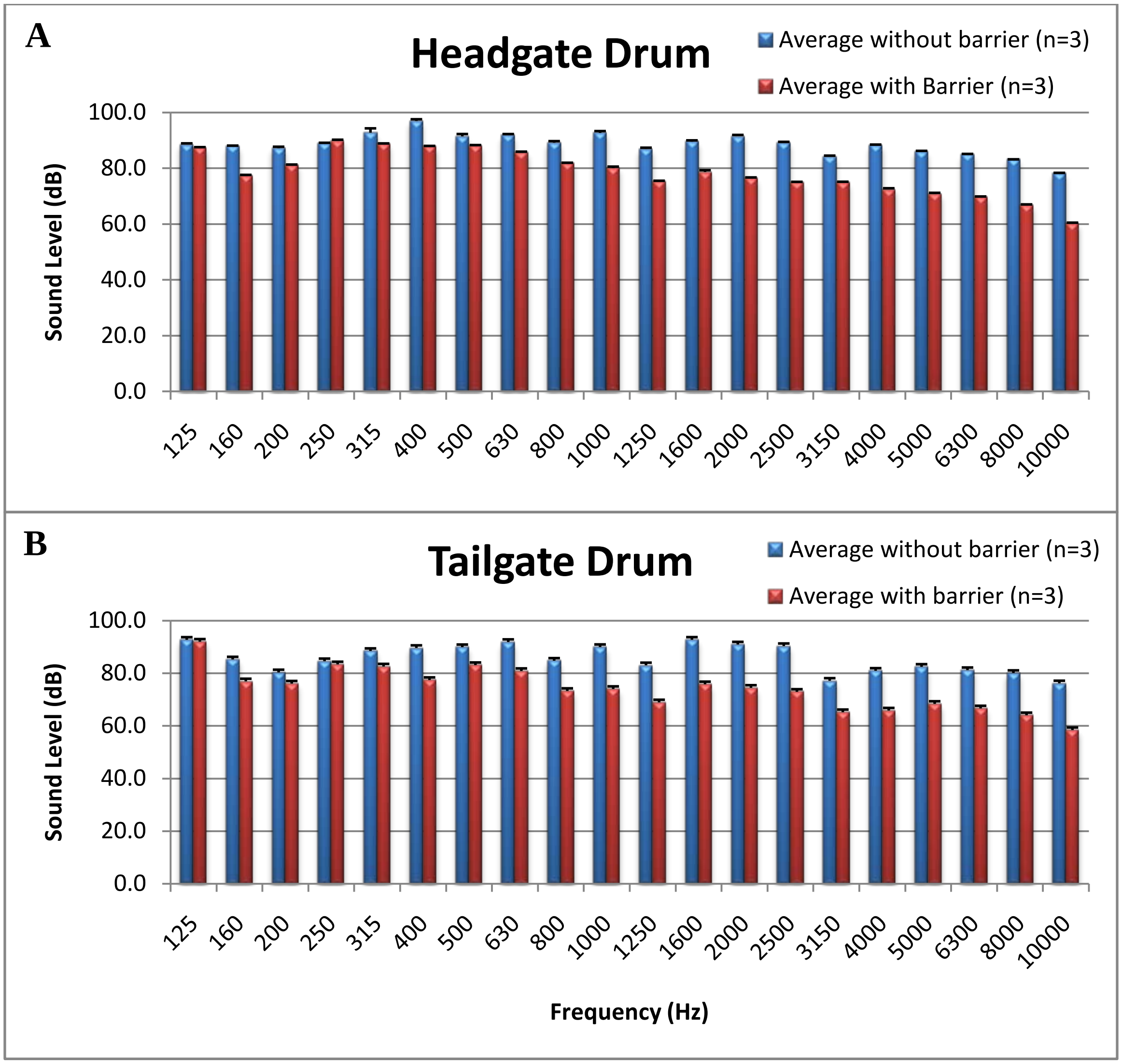


Figure 17: Frequency measurements with and without plywood barrier

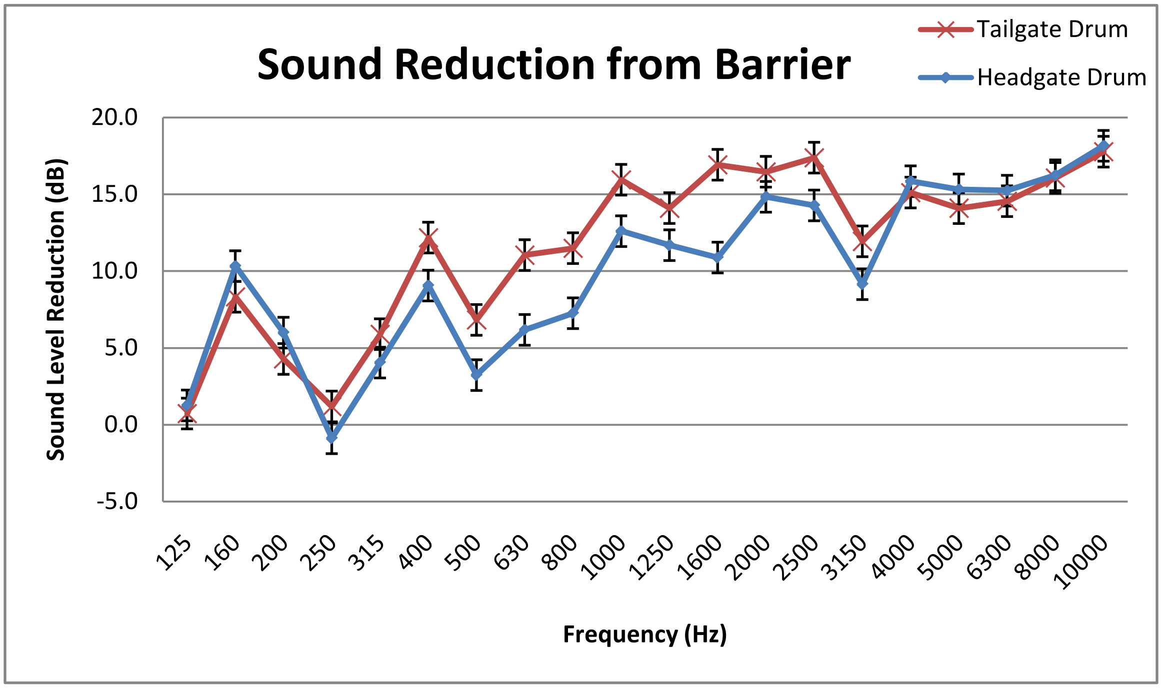


Figure 18: Mean sound level reduction for plywood barrier (n=3)

Sound Intensity Measurement

The sound intensity was measured with the Norsonic sound meter in conjunction with the sound intensity probe as described in the methods section of this document. The total surface area of the box surrounding the speaker set was 17.22 m^2. The measured results are reported in tables 4 and 5 below for the headgate and tailgate speakers, respectively. The sound intensity reported was calculated as the average sound intensity for each measurement using equation (3) of the methods section. The sound power was then calculated using the average sound intensity and equation (2) of the methods section.

Table 4: Sound intensity measurements for the headgate speaker

Surface	Front				Back				Right		Left		Top	Sound Intensity	Sound Power
Frequency	1	2	3	4	1	2	3	4	1	2	1	2	1	(dB)	(dB)
31.5	95	91	87	82	88	86	83	85	86	91	87	91	88	89.1	101.4
63	103	101	94	89	94	93	91	93	91	99	93	97	95	96.6	109.0
125	102	102	93	94	92	95	89	88	89	97	90	98	79	96.3	108.7
250	93	93	91	92	83	77	84	79	88	89	87	90	85	89.1	101.5
50	97	97	93	94	83	81	86	87	87	89	87	90	89	91.7	104.1
1000	90	90	88	89	79	75	75	68	80	81	77	84	81	85.0	97.4
2000	82	82	84	87	78	73	76	71	72	72	78	72	78	80.3	92.7
4000	67	71	80	83	63	60	68	65	65	63	67	66	69	74.0	86.4

Table 5: Sound intensity measurements for the tailgate speaker

Surface	Front				Back				Right		Left		Top	Sound Intensity	Sound Power
Frequency	1	2	3	4	1	2	3	4	1	2	1	2	1	(dB)	(dB)
31.5	82	89	82	80	87	85	83	84	86	93	85	90	85	87.0	99.3
63	92	100	89	82	95	95	92	93	93	100	92	98	95	95.4	107.8
125	96	101	94	93	93	92	85	84	92	98	87	98	86	94.8	107.2
250	90	92	91	88	81	82	77	82	89	87	87	89	84	87.9	100.2
50	92	96	92	89	84	84	83	79	89	90	88	90	88	90.0	102.3
1000	88	89	88	86	77	77	73	76	80	80	81	84	83	83.9	96.2
2000	80	82	83	79	73	71	70	74	74	72	76	74	75	77.4	89.8
4000	65	66	78	73	67	64	60	64	67	55	65	59	64	69.2	81.6

Room Absorption Coefficient

The room absorption coefficient was measured and calculated from the 27 sound level measurements taken at various locations in the room. The buzzer was run continuously during the measurements and each sound level measurement was recorded as a 10 second average sound pressure level. The results of the measured TA are shown in table four and compared to the calculated TA. Published sound-absorption coefficients (α) for suspended acoustical tile for the ceiling, ceramic tile for the floor, and shredded wood fiberboard for the walls where used to calculate the room TA (Bruce, Bommer, &

Moritz, 2003). Each α was multiplied by the total surface area for each section, for example, the ceiling surface area was 101 m^2, multiplied by an α of 0.76 for the 125 Hz frequency to give a TA of 77 metric sabuns. The total room TA is the some of the ceiling, floor, and wall TA's.

Table 6: TA at WPAFB test facility
*The α for 8000 Hz was estimated

Frequency (Hz)	125	250	500	1000	2000	4000	8000*
Ceiling Surface Area (M^2)	101	101	101	101	101	101	101
Ceiling α	0.76	0.93	0.83	0.99	0.99	0.94	0.94
Calculated Ceiling TA (metric sabuns)	77	94	84	100	100	95	95
Floor Surface Area (M^2)	101	101	101	101	101	101	101
Floor α	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Calculated Floor TA (metric sabuns)	1	1	1	2	2	2	2
Wall Surface Area (M^2)	127	127	127	127	127	127	127
Wall α	0.32	0.37	0.77	0.99	0.79	0.88	0.88
Calculated Wall TA (metric sabuns)	41	47	98	126	100	112	112
Calculated Room TA (metric sabuns)	118	142	183	228	202	209	209
Measured Room TA (metric sabuns)	4.3	4.1	15.2	18.3	11.5	13.9	5.5
Difference	114	138	168	210	191	195	204

Calculations

The predicted noise reduction from the barrier was calculated as described in the methods section. The overall sound level was calculated as the logarithmic sum of the three sources, the diffracted noise over the barrier, the reflected noise off the ceiling, and the secondary diffuse noise source, which was the second speaker set (Table 7).

Table 7: Calculated sound levels with the barrier in place

Sound source	Headgate with barrier (dB(A))	Tailgate with barrier (dB(A))
Diffracted	83.1	80.2
Reflected from ceiling	81.0	78.2
Second Speaker	85.3	87.0
Total Calculated Sound Level	88.2	88.3

Table 8: Actual versus measured insertion loss

	Measured Sound level w/o barrier (dB(A))	Measured Sound Level w/ barrier (dB(A))	Calculated sound level w/ barrier (dB(A))	IL from measured sound level (dB)	IL from Calculated Sound Level (dB)	Percent Difference (%)
Headgate	103.1	92.8	88.2	10.3	14.9	44.7
Tailgate	100.3	87.1	88.3	13.2	12.0	9.1

Table 8 compares the sound level without the barrier to the measured sound level with the barrier in place and the calculated sound level with the barrier in place. The model predicted the tailgate insertion loss to within 1.2 dB(A) and the headgate insertion loss within 4.6 dB(A). Figure 19 shows the full octave band analysis for measured versus calculated noise reduction levels.

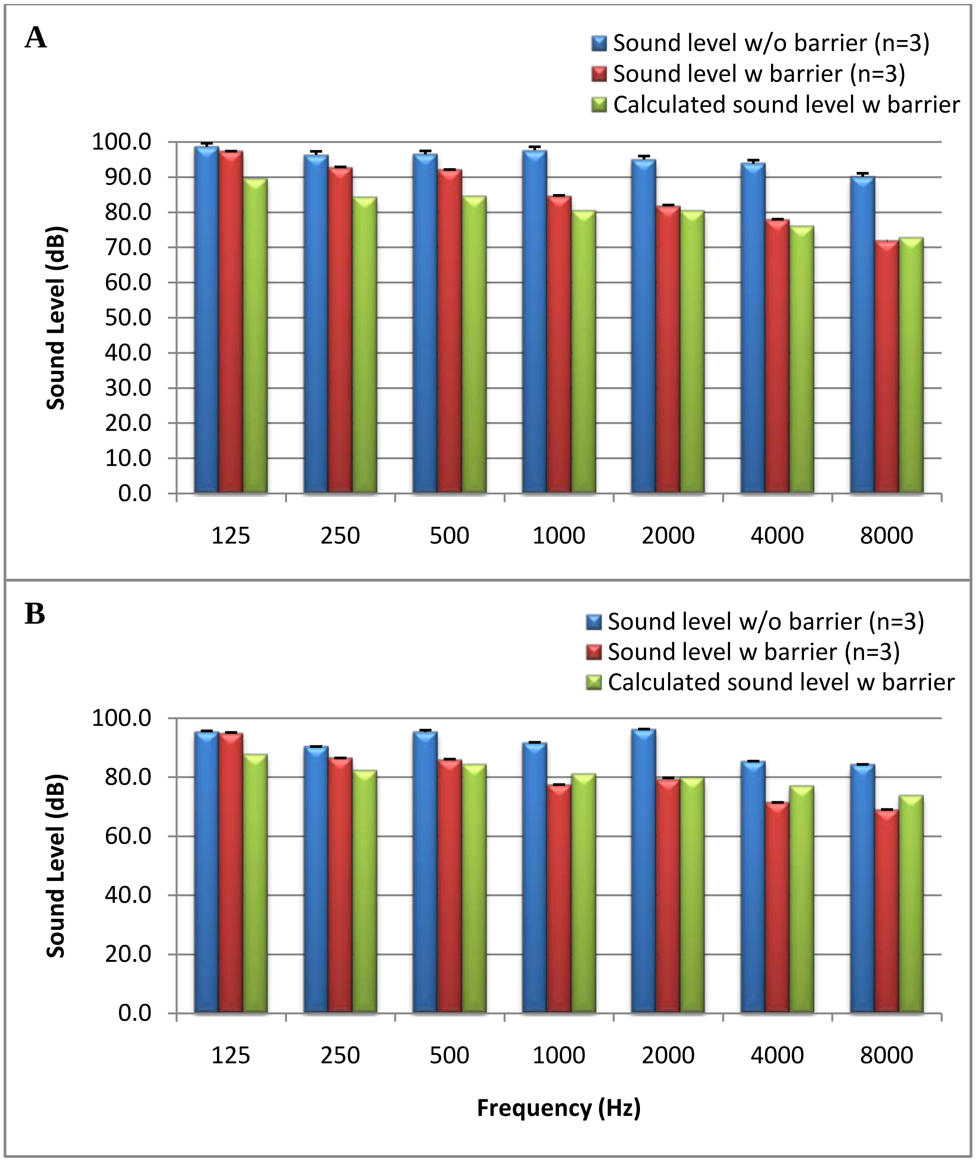


Figure 19: Sound reduction for center octave band analysis. A: Measured at the headgate drum position. B: Measured at the tailgate drum position

Testing at the NIOSH-PRL Facility

Sound Testing

The overall logarithmic average noise reduction for the barrier for all recordings combined was 4.5 ± 2.8 dB(A). The full barrier, essentially a wall, had the greatest sound attenuation for all locations. The partial barrier for all configurations had some

noise reduction, but was not as effective as the full barrier. Additionally, the pink noise had a higher reduction than the shearer operation noise. Separating the barrier into two categories, full and partial, produced a reduction of 7.6 ± 3.5 dB(A) and 4.2 ± 2.4 dB(A), for the pink noise and 5.6 ± 0.3 dB(A) and 2.2 ± 0.5 dB(A) for the shearer noise, respectively. Figure 20 shows a typical example of the noise reduction from the different barrier configurations. This particular example is taken at the headgate position (Fig 14) with the cutting drum in the up position for the shearer noise.

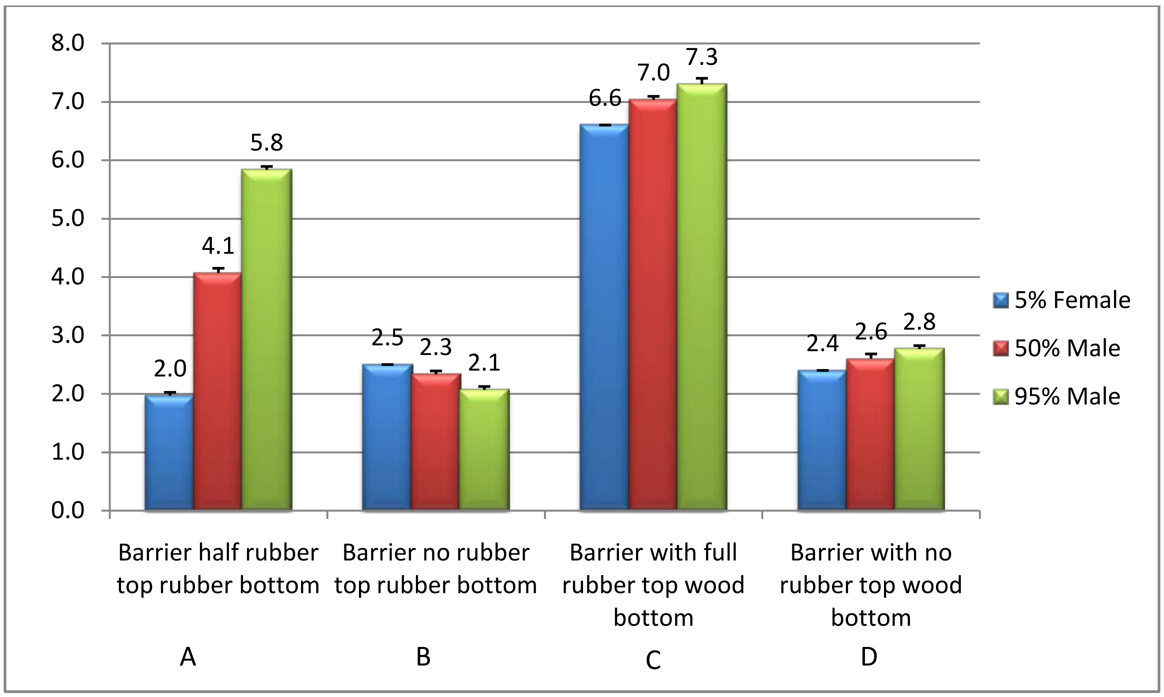


Figure 20: Example of noise reduction from the various barrier configurations

The remainder of the noise data for each position can be found at appendix A.

The results of the TA measurement are shown in table 9. Due to the complexities of sound absorption in the test facility such as the simulated shearer and cutting drums, the simulated barriers and shields and the open spaces, an α for the face could not be accurately calculated to compare to the α reported for coal mines walls. However, using

the published α and the mine dimensions (Kovalchik, Matetic, Cole, & Smith, 2007), a TA can be calculated from the underground tests and compared directly to the TA from the NIOSH-PRL test facility. Except for the lowest frequency, 125 Hz, the test facility was more reflective (less absorptive) than the underground mine. Therefore, the barrier may be considerably more effective at reducing noise exposure underground as compared to the reduction realized in the test facility.

Table 9: Measured TA at NIOSH-PRL test facility

Frequency (Hz)	125	250	500	1000	2000	4000	8000
Measured TA buzzer in the middle (metric sabuns) (n=20)	24.1	5.6	8.7	9.6	12.3	25.1	7.9
Measured TA for buzzer at face (metric sabuns) (n=10)	17.3	14.8	11.6	4.4	7.0	23.6	9.4
Average (metric sabuns) (n=30)	21.9	8.6	9.7	7.9	10.5	24.6	8.4
Mine Surface Area (m^2)	290	290	290	290	290	290	290
Reported coal face α	0.04	0.20	0.14	0.15	0.19	0.28	0.45
Calculated mine shaft TA based on published α (metric sabuns)	11.6	52	40.6	43.5	55.1	81.2	130.5
Difference from test facility (metric sabuns)	5.7	-43.4	-30.9	-35.6	-44.6	-56.6	-122.1

Dust Testing

The results of each ten minute test session were compiled to obtain an average (n=300) respirable dust exposure level in mg/m^3. Results were compared for statistical significance using JMP® software (SAS Institute Inc., Cary, North Carolina). Each configuration was compared using Analysis of Variance (ANOVA) with a significance level of alpha less than 0.05. When a significant difference was observed between groups, Tukey-Kramer comparisons were used to determine which configuration within the group showed a statistically significant difference.

The greatest reduction in measured dust levels was at the headgate position with the low ventilation face velocity. The reduction was from 39 mg/m^3 without the barrier to 1.5 mg/m^3 with the partial barrier, equating to a 96 percent reduction. Similar reductions were noticed at the mid and high ventilation velocities for the headgate position, bringing the dust levels close to zero with either barrier in place. At the remaining two shearer operator positions, dust levels also decreased significantly with both the partial and full barriers as compared to no barrier for all ventilation rates (Prob > F 0.0001 for all cases). Although in most cases, a significant difference was also found between the dust levels for the partial versus the full barrier, these differences were not of practical significance. Figure 21 summarizes the dust level results.

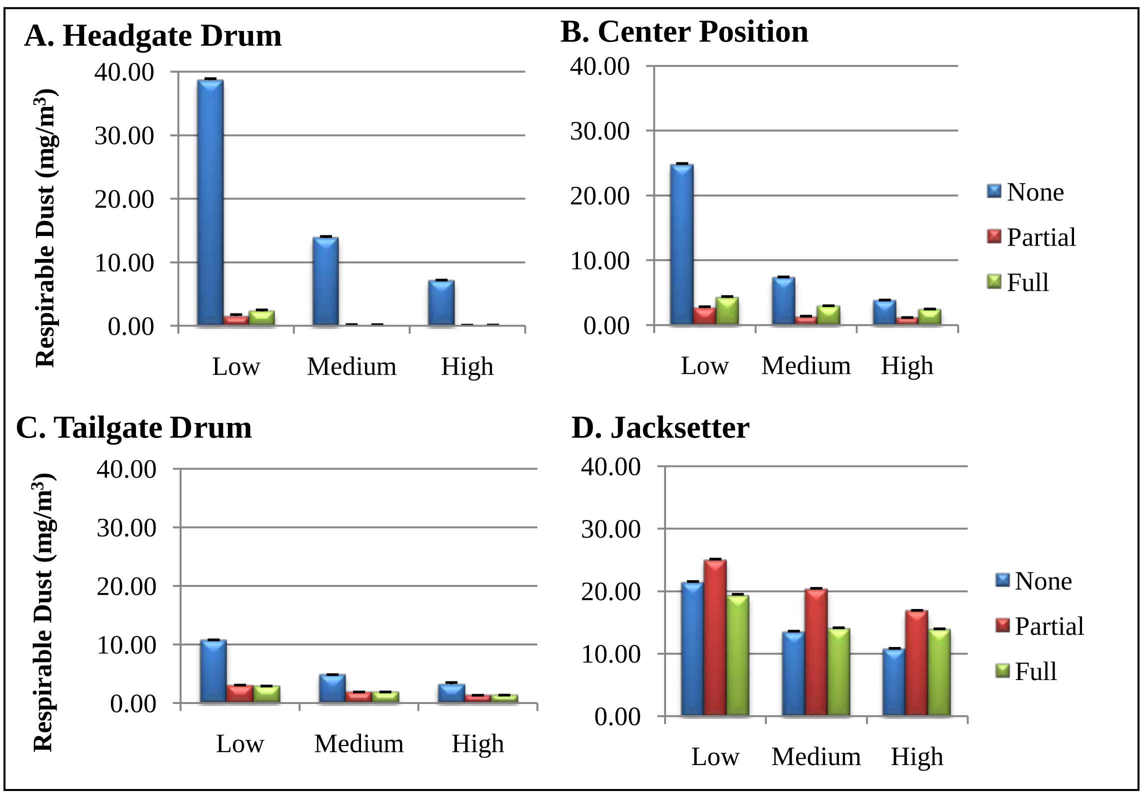


Figure 21: Respirable dust levels for low, medium, and high relative face velocities

For the jacksetter position, the dust levels increased significantly with the placement of the barrier, with the exception of the full barrier at low velocity, which had a significant decrease in dust level (Prob > F 0.0001 for all cases). This can be explained by the dust channeling effect created by the barrier.

One potential drawback to the barrier constructed in this investigation may be the reduced visibility of the cutting drum from the operator position. Figure 22 demonstrates the visibility of the cutting drum while the dust was being generated. Although the coal dust adhered to the acrylic sheeting, a simple wash spray could be utilized to keep the shield clean. Additionally, if the barrier was configured without the rubber top, the majority of the operators would be able to simply look over the top of the barrier to see the top of the cutting drum.

Figure 22: View of headgate cutting drum through partial barrier

5. Discussion

WPAFB Sound Tests

The initial above ground tests performed at WPAFB showed a 10.3 and 13.2 dB(A) insertion loss for the tailgate and headgate operator position. The measured results varied slightly from the predicted calculated values. The predicted loss at the headgate drum was 14.9 dB(A) and at the tailgate was 12.0 dB(A). The predicted loss calculated in table 5 was calculated using the TA determined from the published absorption coefficients. Because of the large discrepancy between the calculated TA and the measured TA, the expected IL was recalculated using the measured TA. The result of the predicted IL using the measured TA gives quite different results as shown in table 10. In this case, the room is much more reflective than previously predicted; therefore the contribution of sound from the second speaker is greater in the calculations.

Table 10: Predicted vs. measured IL using measured TA

	Measured Sound level without barrier (dB(A))	Measured Sound Level with barrier (dB(A))	Calculated sound level with barrier (dB(A))	IL from measured sound level (dB)	IL from Calculated Sound Level (dB)	Percent Difference (%
Headgate	103.1	92.8	98.3	10.3	4.8	114
Tailgate	100.3	87.1	99.7	13.2	0.6	250

Using the measured TA increased the difference between the predicted and actual IL. This difference in the IL may be explained with the fact that the sound produced by the speakers is very directional. Therefore, the majority of the sound level at each location is the contribution of the speaker directly in front of the sound level meter. Thus, a barrier placed between the speaker and meter would have a higher IL than predicted. This effect can also account for the differences between the headgate position and tailgate position. The IL has a larger discrepancy between predicted and calculated at the tailgate position. By observing the room configuration (Fig 23), it can be expected

the headgate drum speaker will diffuse the sound throughout the room to a greater extent than the tailgate drum position.

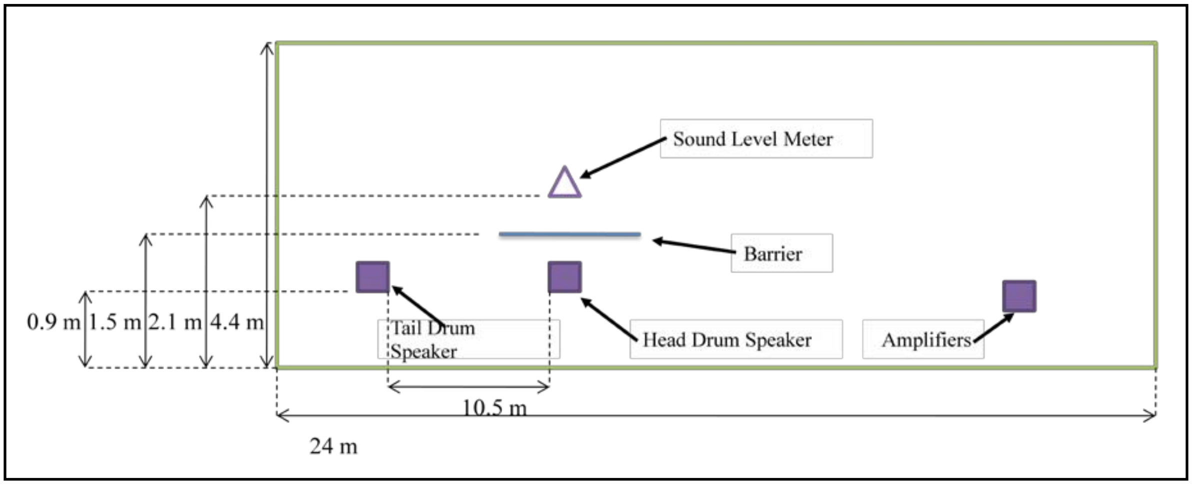


Figure 23: WPAFB test configuration

As already mentioned, the calculated room TA differed from the measured TA. The difference may be explained in part from the absorptive wall material being coated with several layers of paint, thus losing any absorptive properties. Thus showing the TA calculations may be useful for design or comparison purposes, but may not be reliable when a material has changed from its original sound absorption properties.

NIOSH-PRL Sound Tests

The full scale model at the NIOSH-PRL test facility IL was slightly lower than the WPAFB test, with a 5.6 dB(A) and 2.4 dB(A) reduction for the recorded shearer noise for the full and partial barrier, respectively. According to the U.S. Code of Federal Regulations (CFR), Title 30, Part 62.130, “if during any work shift a miner's noise exposure exceeds the permissible exposure level, the mine operator must use all feasible engineering and administrative controls to reduce the miner's noise exposure to the

permissible exposure level” (MSHA, 2000). MSHA gives further guidance that an engineering control is feasible if it reduces the noise exposure, is technologically achievable, and is economically achievable (MSHA, 2000). The MSHA guide also states that a 3 dB(A) reduction is generally considered to have reduced the noise, but the control may still be considered feasible if in combination with other controls, it achieves a minimum of 3 dB(A). Although the partial barrier did not meet the 3 dB(A) reduction criteria, combined with the dust level reduction, it could be considered a feasible control and tested underground during an actual longwall operation. When considering the NIOSH-PRL test facility was more reflective than the underground coal mine, a further reduction in noise may be expected in actual shearer operations. Additionally, considering the underground test was performed in a coal shaft with four coal surfaces without the open gop space normally found behind the shearer during actual shearer operations, the reduction may be even greater because of the potentially higher absorption coefficient.

The four different partial barrier configurations tested for noise reduction all reduced the sound level to the operator. However, each partial barrier configuration had slightly different results, while the full barrier was much different. When looking at the percentage of a barrier, with the full barrier area considered 100% and a transmission loss of 7 dB(A), the expected loss for the partial configurations would be 5.5, 4.8, and 6.0 dB(A) for the half rubber top barrier (Fig 20A), the no rubber top (Fig 20B), and the wood bottom (Fig 20D), respectively. The actual noise reduction for configurations A, B, and D were approximately 4, 2, and 2.5 dB(A). This may suggest the noise reflected of the ceiling and floor was a large contributor to the overall noise level. Although probably not a practical application for underground longwall mining, the full barrier,

essentially a wall, had the greatest reduction. This was due to the sound source being isolated from the operator by the wall, showing that when possible, even a simple wall isolating a sound source can achieve a high level of noise reduction. The partial barriers all had similar sound level reduction, indicating the sound was either passing over or under the barrier, or both, depending on the configuration. In the underground operation where operators are routinely exposed to hazardous noise at 151 percent of the allowable limit (roughly 93 dB(A) continuous equivalent level) (Joy & Middendorf, 2007), the barrier may reduce the noise to levels near the allowable limit, thereby reducing the frequency of NIHL.

NIOSH-PRL Dust Tests

The results indicated that a significant reduction of respirable dust can be achieved from either a partial or full barrier mounted between the cutting drums of the longwall shearer and the shearer operator. As high as a 96 percent reduction in respirable dust levels was measured at the shearer operators' position. Additionally, reduced dust levels were noticed regardless of ventilation face velocity. While the model used in this study was not built to withstand the rigorous conditions found in underground longwall operations, the model demonstrates the preliminary feasibility of such a control. In order to be of practical use, the barrier would need to be constructed of hardened materials, such as a bullet-proof clear acrylic, be mounted on a flexible hinge, and be capable of continuous or rapid cleaning so as not to block the operator's view of the longwall face.

Surprisingly, for the dust reduction, the partial and full barriers had nearly identical dust reduction levels at all positions and ventilation rates, suggesting the barrier in either configuration helps keep a laminar flow separation between the dust source, the

cutting drum, and the shearer operator. This is a significant finding, showing even the partial barrier will dramatically reduce dust levels to the miners. As mentioned earlier, an estimated 20 percent of coal mine longwall shearer operators continue to be overexposed to dust levels, and eight percent of long term operators suffer from coal worker pneumoconiosis (CWP) (Rider & Colint, 2001). With the application of this barrier in conjunction with water spray nozzles, it may be possible to eliminate over-exposure to dust levels, thus reducing future cases of CWP.

Additional Noise Barrier Modeling

The barrier modeling used in this thesis was not only inaccurate, but would not be a practical tool for the base level BEE. Therefore, a simpler model was developed assuming a free field with the only sound sources being the diffracted noise over the barrier and the reflected noise off the ceiling. Equation 4 presented earlier in this document was used in a Microsoft Excel® spreadsheet along with the insertion loss value from table 21.11 of *The Occupational Environment* (Bruce, Bommer, & Moritz, 2003). The only inputs needed from the user are source, receiver, barrier, and ceiling height, ceiling material, and an octave band analysis of the sound source. This simpler model provided closer results to the realized sound reduction, thus validating the model in the two locations tested in this study. Table 11 outlines the results of using this new model. Because the model assumes a perfect barrier from the floor up, configuration D from the NIOSH-PRL test was used in the model. Configuration D was the full plywood to the floor in combination with the acrylic, but no rubber top (Fig 20D). Figure 24 shows the model results for the headgate position with the 50^{th} percentile male.

Table 11: Measured versus predicted loss using simplified model

Test	Predicted Loss dB(A)	Measured Loss dB(A)	Percent Difference (%)
WPAFB headgate	12	10.3	16.5
WPAFB tailgate	15	13.2	13.6
NIOSH-PRL headgate	2.9	2.6	11.5
NIOSH-PRL center	1.8	2.1	14.3
NIOSH-PRL tailgate	3.2	0.7	350

The following decision matrix and barrier modeling can be used to help dtermine if a barrier can be ean effective engineering control

Decision Matrix		
1. Is a barrier physically possible?	Yes	Proceed to Question 2
2. Will the worker accept a barrier?	Yes	Proceed to Question 3
3. Is the hazard source stationary or semi-stationary?	Yes	Proceed to Question 4
4. Is this for noise or dust control?	Noise	Proceed to Question 5
5. Can the barrier be modeled?	Yes	Proceed to Modeling Sheet
6. Does model indicate a 3dB(A) reduciton or greater?	Yes	Test Barrier
7. Is cross ventilation available to channel dust away from op	Yes	Test Barrier

NOTE: These Calculations assume a perfect barrier in a free field, the predicted sound reduction may be less than the observed
All Measurements must be input in meters

Area Data	
Height of Source (m)	1
Height of Receiver (m)	1.6
Height of Barrier (m)	2.4
Line of sight distance between source and receiver (m)	3.3
Height of ceiling (m)	3
Ceiling material (pick from dropdown)	Plywood

Octave Band Measurement of Source									
Freqeuncy	**31.5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Octave Band Measurement of Source	77.0	94.9	93.6	78.4	80.6	74.8	76.0	73.5	71.5

Results	
Calculated dB(A) without barrier	84
Calculated dB(A) with barrier	81
Reduction dB(A)	3.2

Figure 24: Model for NIOSH-PRL headgate position, 50% male, barrier configuration D

While the simpler version of the model presented here still does not predict the noise reduction within ten percent of the measured value, the model has practical field applications due to its simplicity. The remainder of the results for this new model is in Appendix D.

6. Conclusions

A simulated full scale coal mine longwall shearer operation was utilized to test the feasibility of utilizing a barrier to separate the shearer operator from the direct path of the noise and dust source during mining operations. In this model, noise and dust levels were reduced by the application of a barrier. The barrier should be tested in an underground mining operation to determine if it can reduce the shearer operators' noise and dust exposure to below regulatory limits. If so, the application of the barrier may help reduce the two greatest concerns in the mining industry, NIHL and respiratory diseases.

This proof of concept study helps gain an understanding of how simple engineering controls can be applied to unique industrial operations. As mentioned in the background, the Air Force has not been successful in reducing NIHL claims. Rather, just the opposite has occurred with NIHL claims having increased over the past five or six years, perhaps suggesting current control measures are not effective. Engineering noise controls are often dismissed as being too complicated and expensive to implement. Simple barriers may prove to be useful in AF operations such as aerospace generation equipment (AGE), corrosion control facilities, or any other noisy or dusty operation.

This research addressed a fundamental dilemma within the BEE career field: by regulation, engineering controls are suppose to be the primary means of controlling an occupational exposure to within acceptable limits, yet because engineering controls are often regarded as complicated, expensive, and time consuming, the BEE typically favors PPE, which places the burden of protection on the worker, over a more permanent solution. This research showed proof of concept that even basic noise and dust

engineering controls can be very effective. The developed spreadsheet may be a useful tool for the base level BEE to determine if a sound barrier can be a useful engineering control. Future research could implement the concepts shown in this work to common industrial processes found throughout the AF, with the long range goal of having AF BEEs control processes through engineering measures, rather than just measure exposure and control through PPE. Furthermore, a full scale production model of the longwall barrier should be tested in an actual underground shearer operation.

Appendix A

Table A 1: Initial audio equipment settings

Component	Variable	Setting
Computer	Audio Output	Maximum
Bogen pre-amp	Mic 1	5
	Mic 2-6	Not Used
	Aux 1, Aux 2	Not Used
	Equalizer (#6)	Not Used
	Switch 7	Out
	Switch 9	Out
	Master	2
DBX	Channel 1 Input gain	0
	Channel 1 Cross Over	240 Hz
	Channel 1 Low out gain	-0.5 (1 notch)
	Channel 1 High out gain	-5
	Channel 2 Settings	Not Used
QSC high frequency amp	Channel 1 Gain	22
	Channel 2 Gain	Not Used
QSC low Frequency amp	Channel 1 Gain	14
	Channel 2 Gain	Not Used

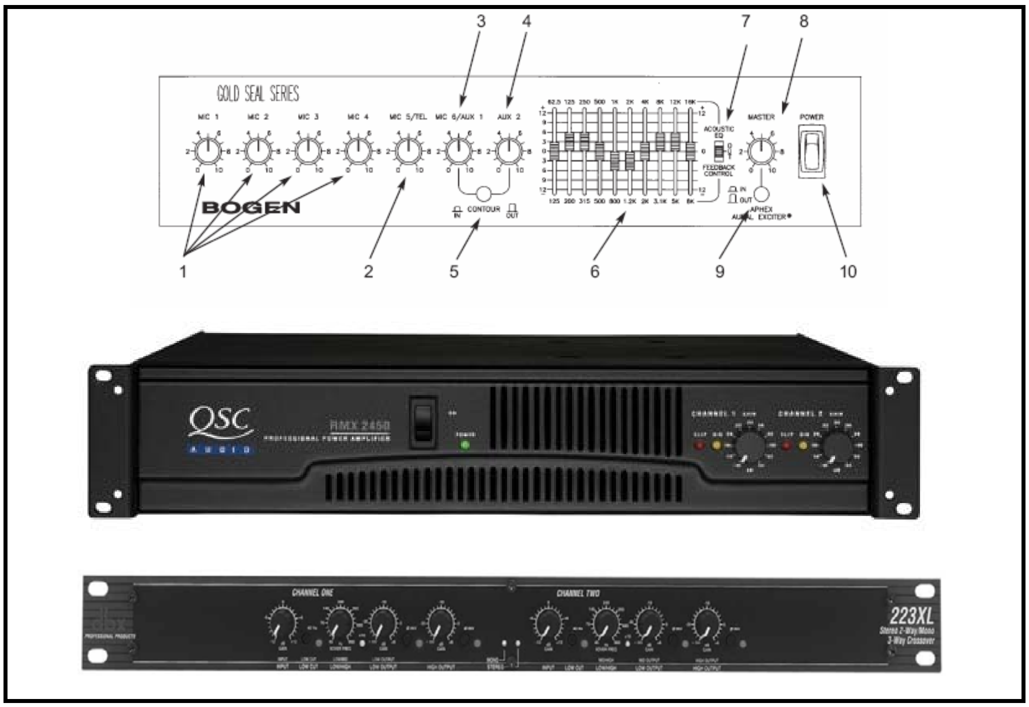


Figure A 1: Front view of audio equipment
(Bogen Communications; QSC Audio; DBX Professional Products)

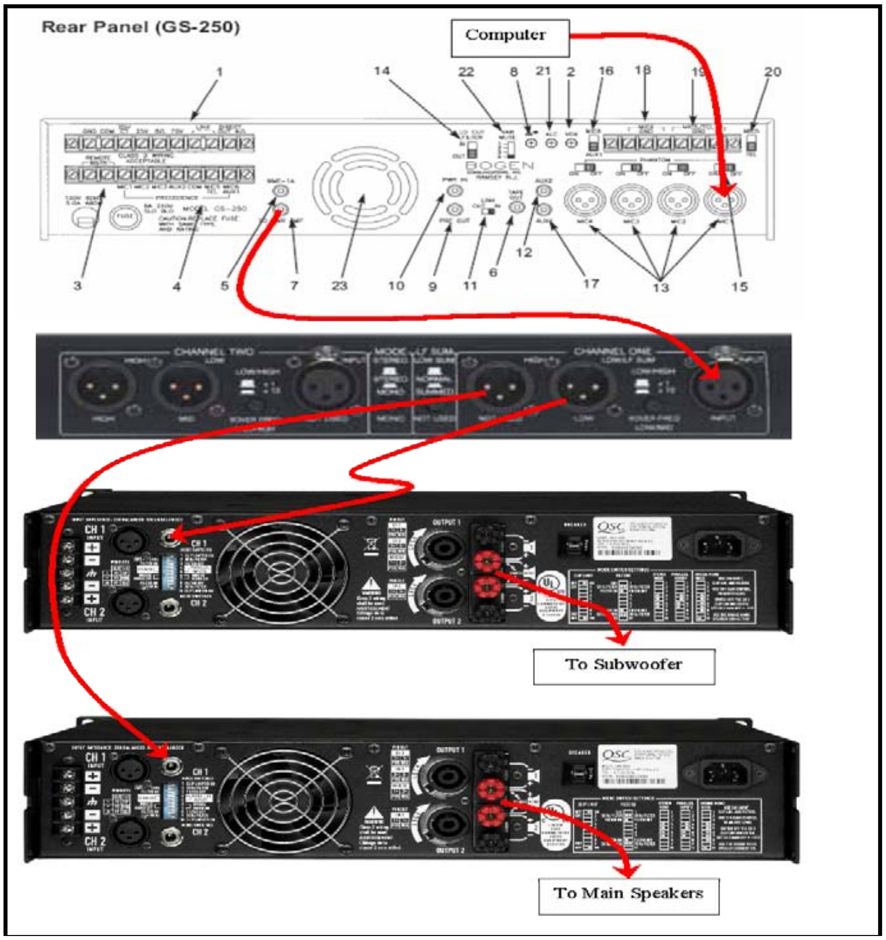


Figure A 2: Rear view of audio equipment
(Bogen Communications; DBX Professional Products; QSC Audio)

Table A 2: Mode switch configuration for amplifiers

Switch Number	Subwoofer Amp	Main Speaker Amp
1	Clip Limiter On	Clip Limiter On
2	30 Hz	50 Hz
3	Filter On	Filter On
4	Parallel	Parallel
5	Parallel	Parallel
6	Bridge Mono On	Bridge Mono On
7	Bridge Mono On	Bridge Mono On
8	Not Used	Not Used
9	Not Used	Not Used
10	Not Used	Not Used

Appendix B

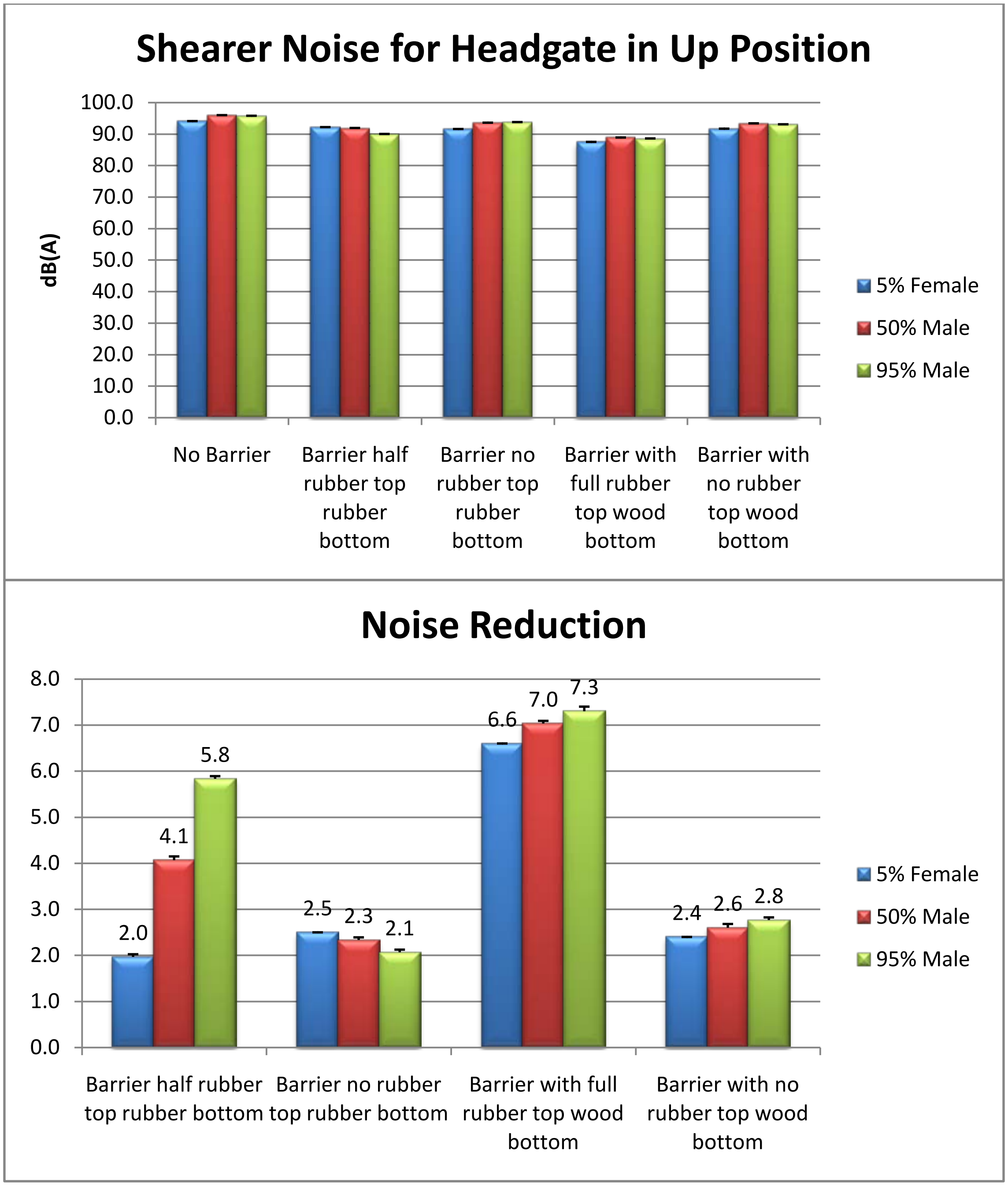


Figure B 1: Recorded shearer noise at simulated headgate position

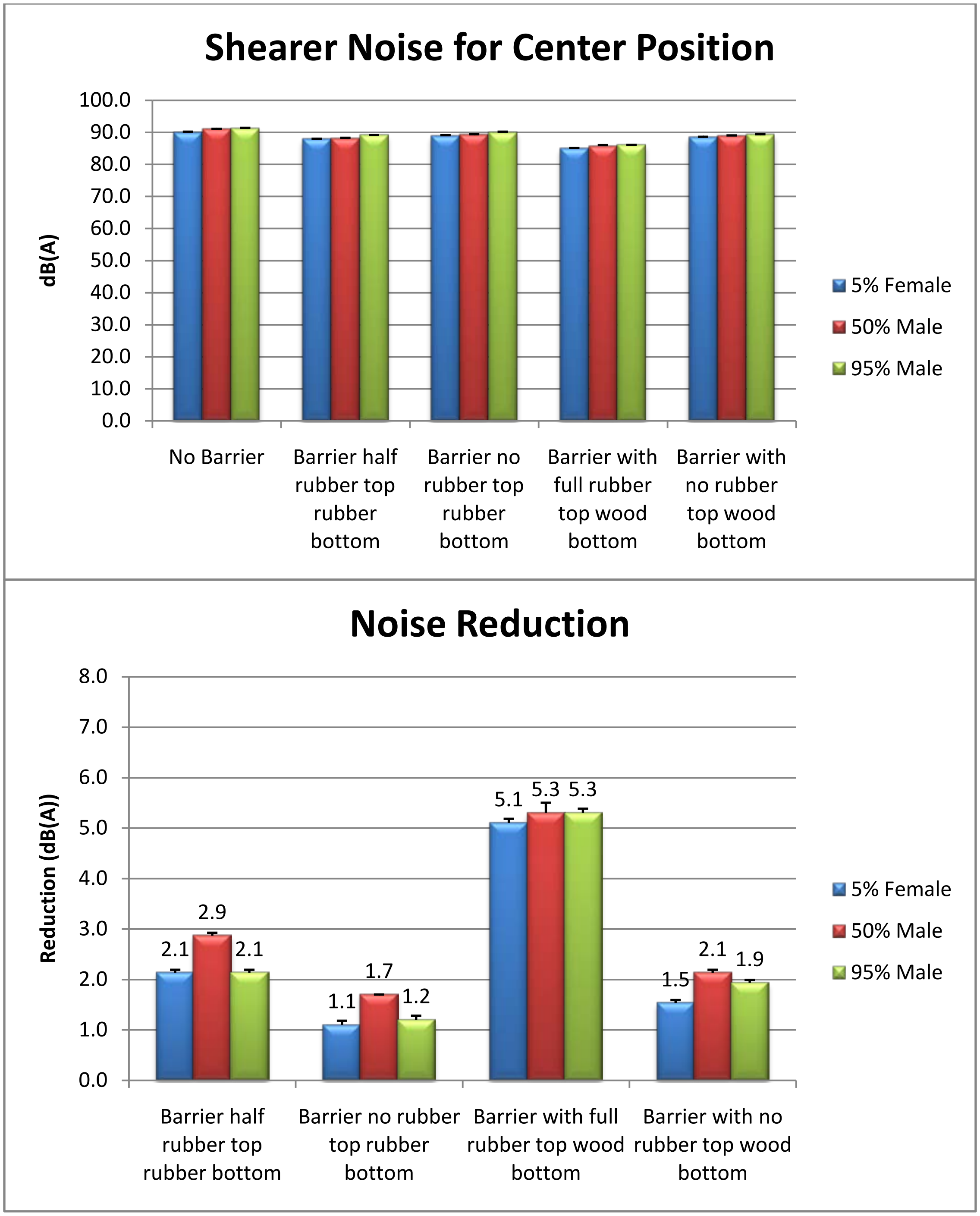
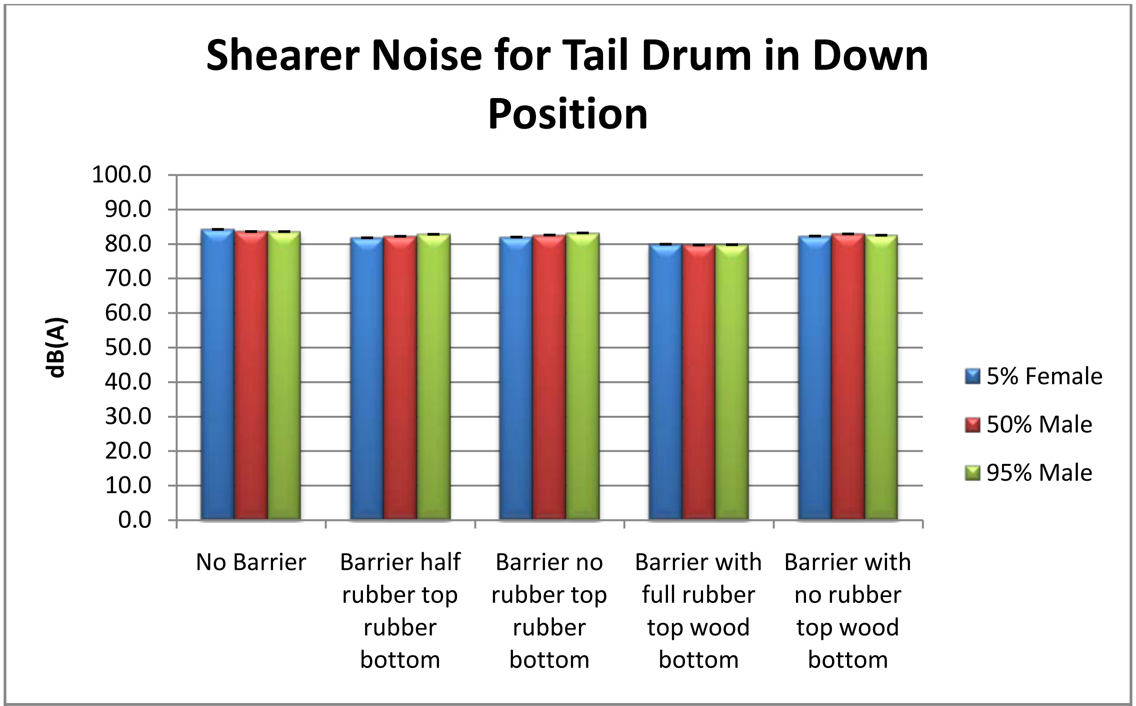


Figure B 2: Recorded shearer noise at simulated center position



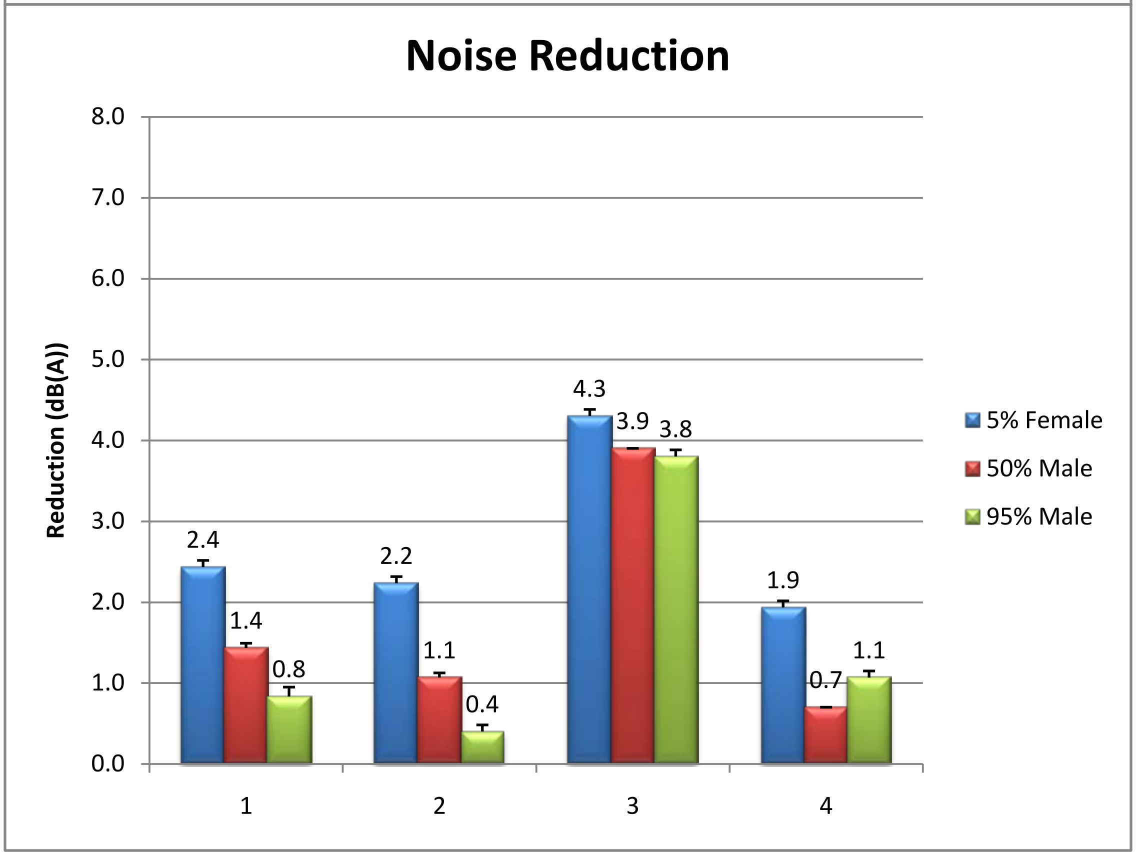


Figure B 3: Recorded shearer noise at simulated tailgate position

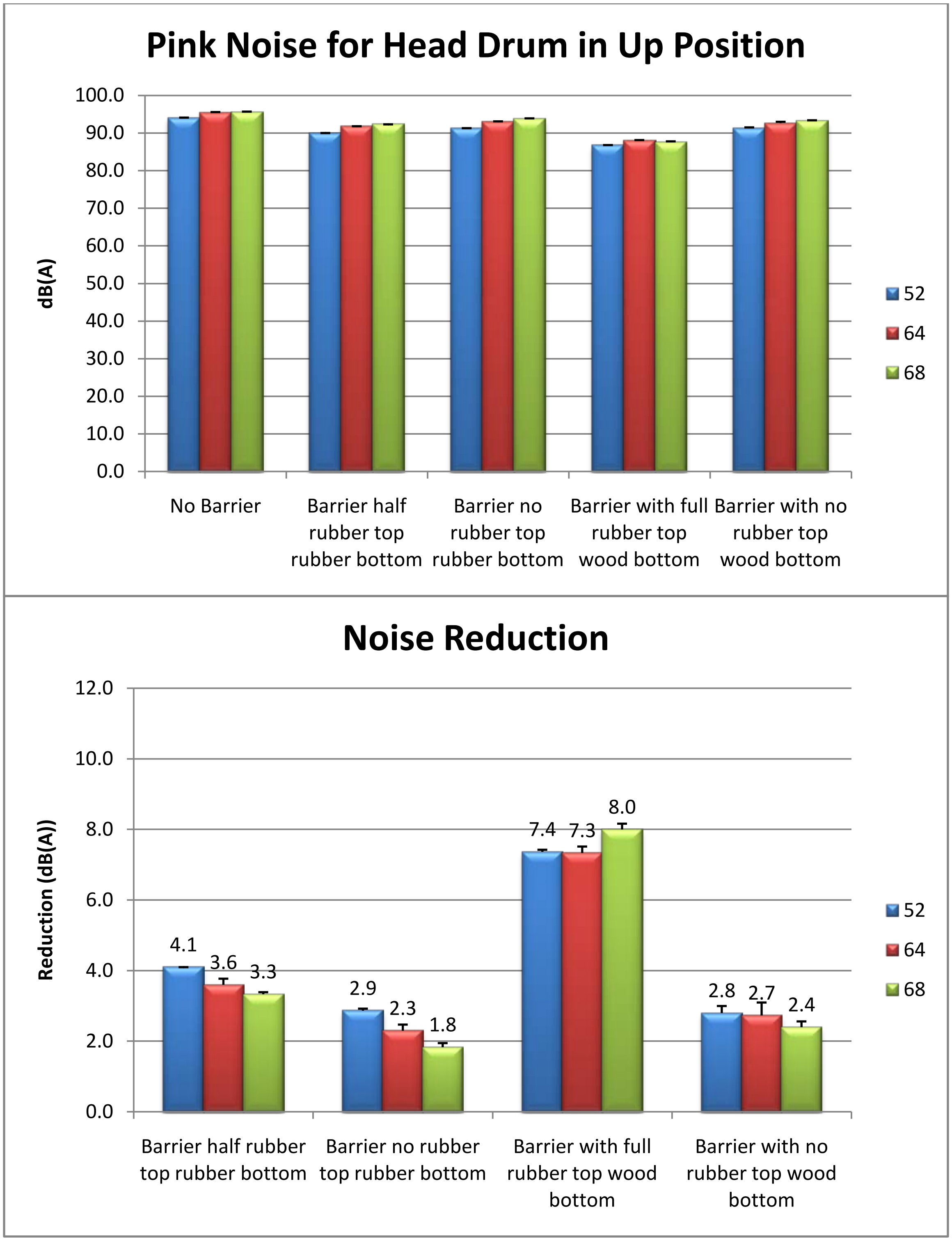
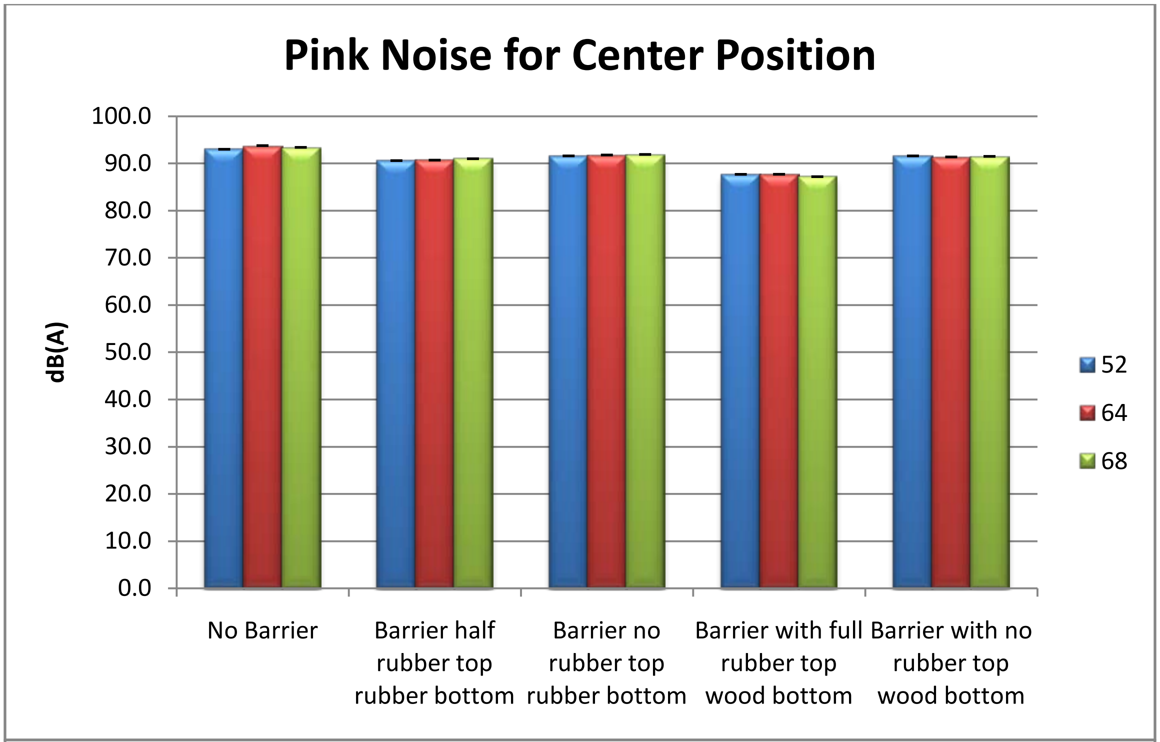


Figure B 4: Pink noise at simulated headgate position



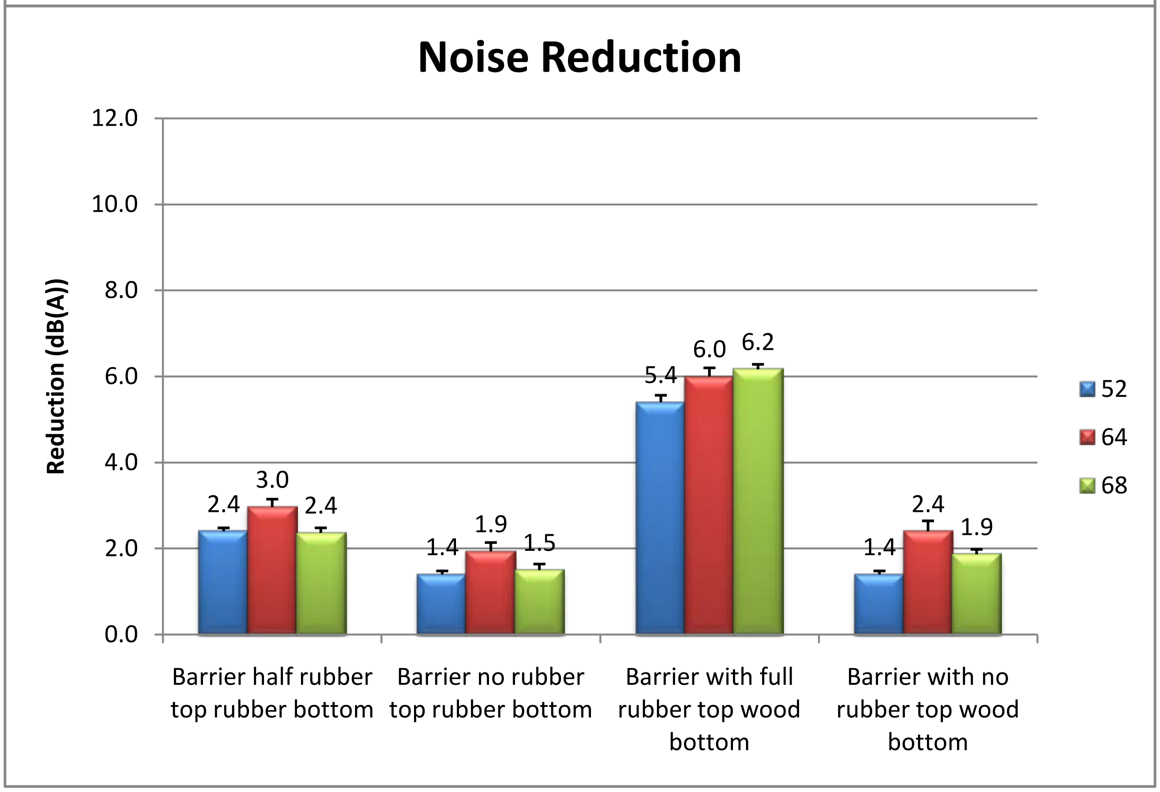


Figure B 5: Pink noise at simulated center position

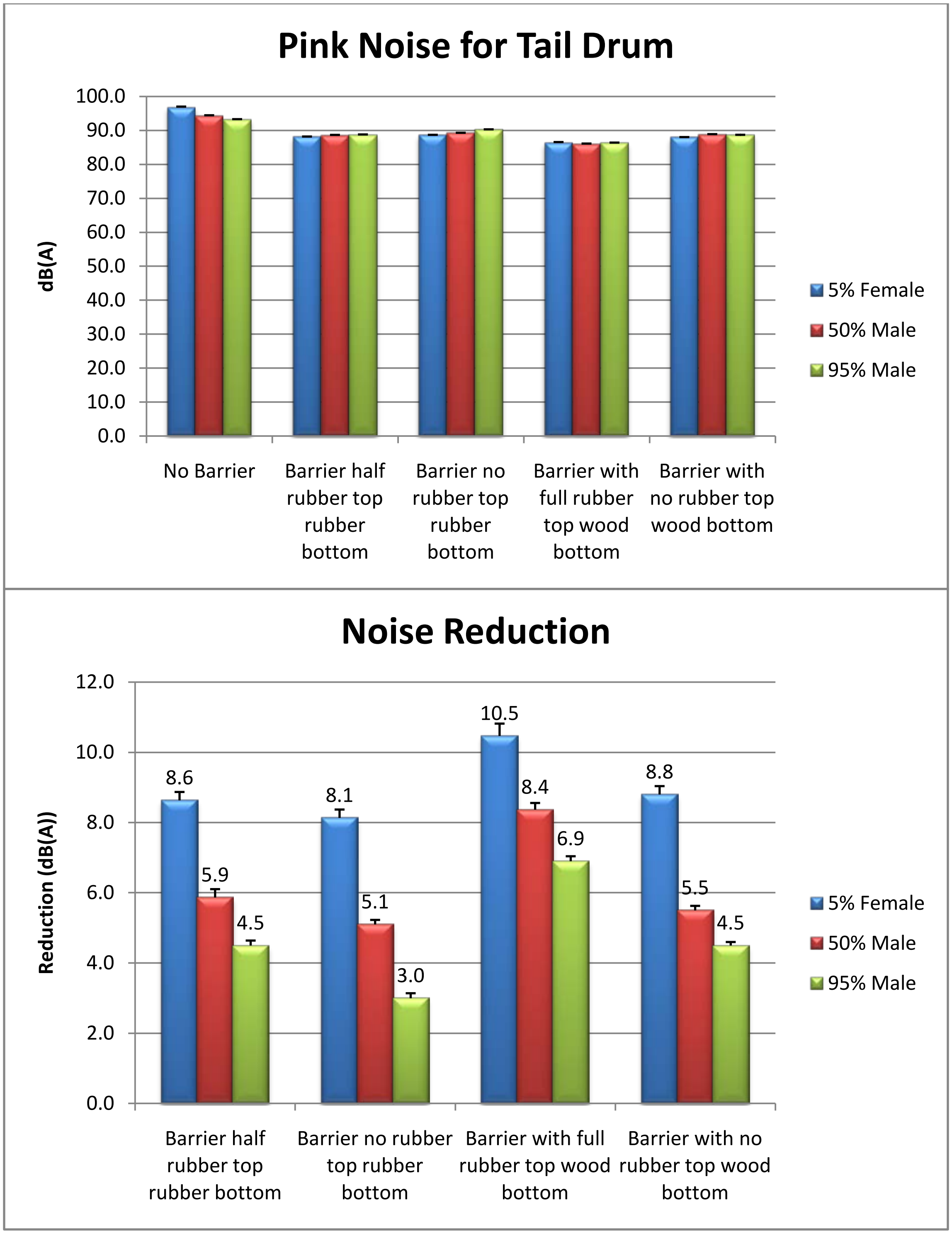


Figure B 6: Pink noise at simulated tailgate position

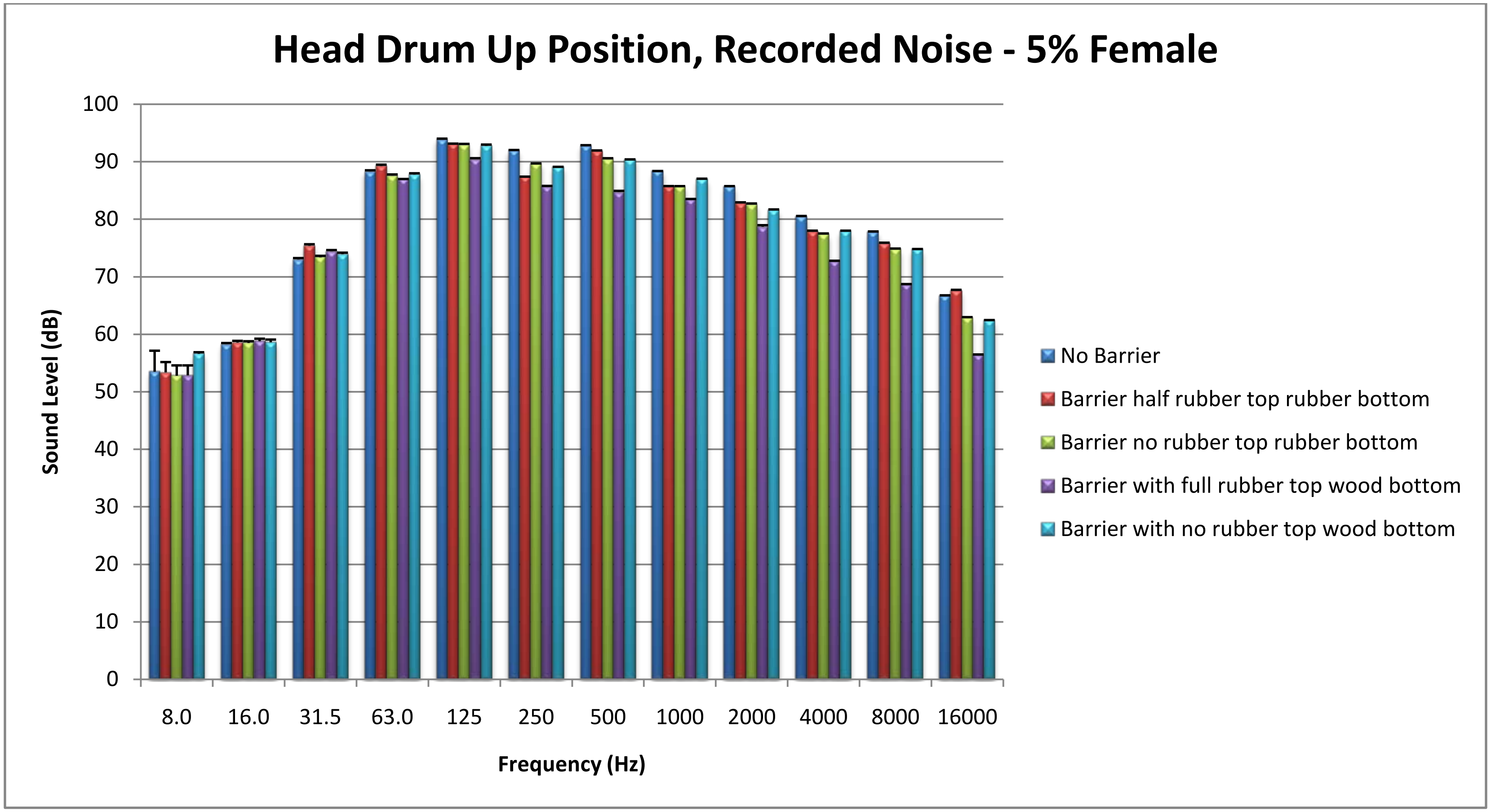


Figure B 7: Octave band analysis headgate drum, recorded noise - 5% female

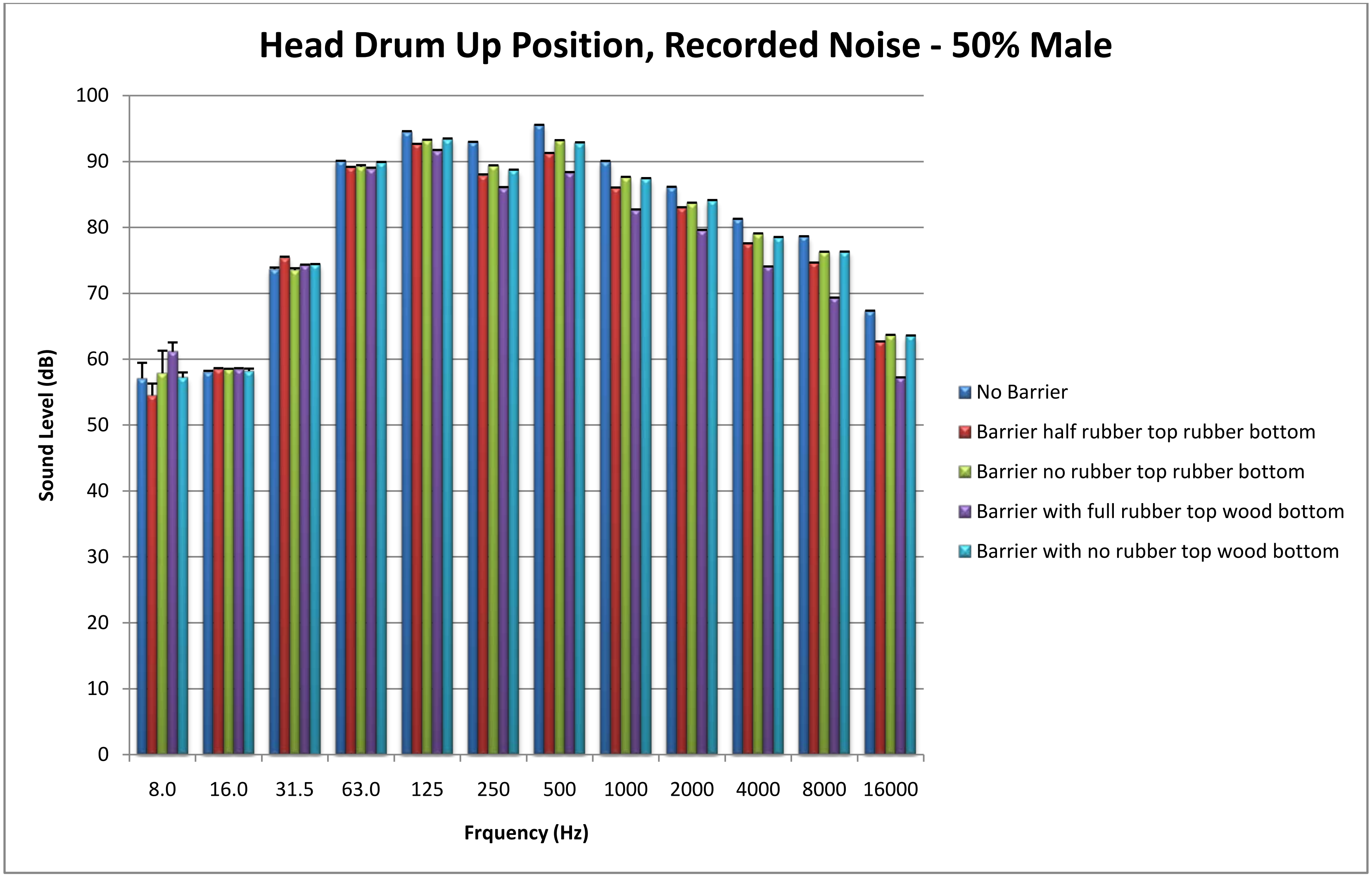


Figure B 8: Octave band analysis headgate drum, recorded noise - 50% male

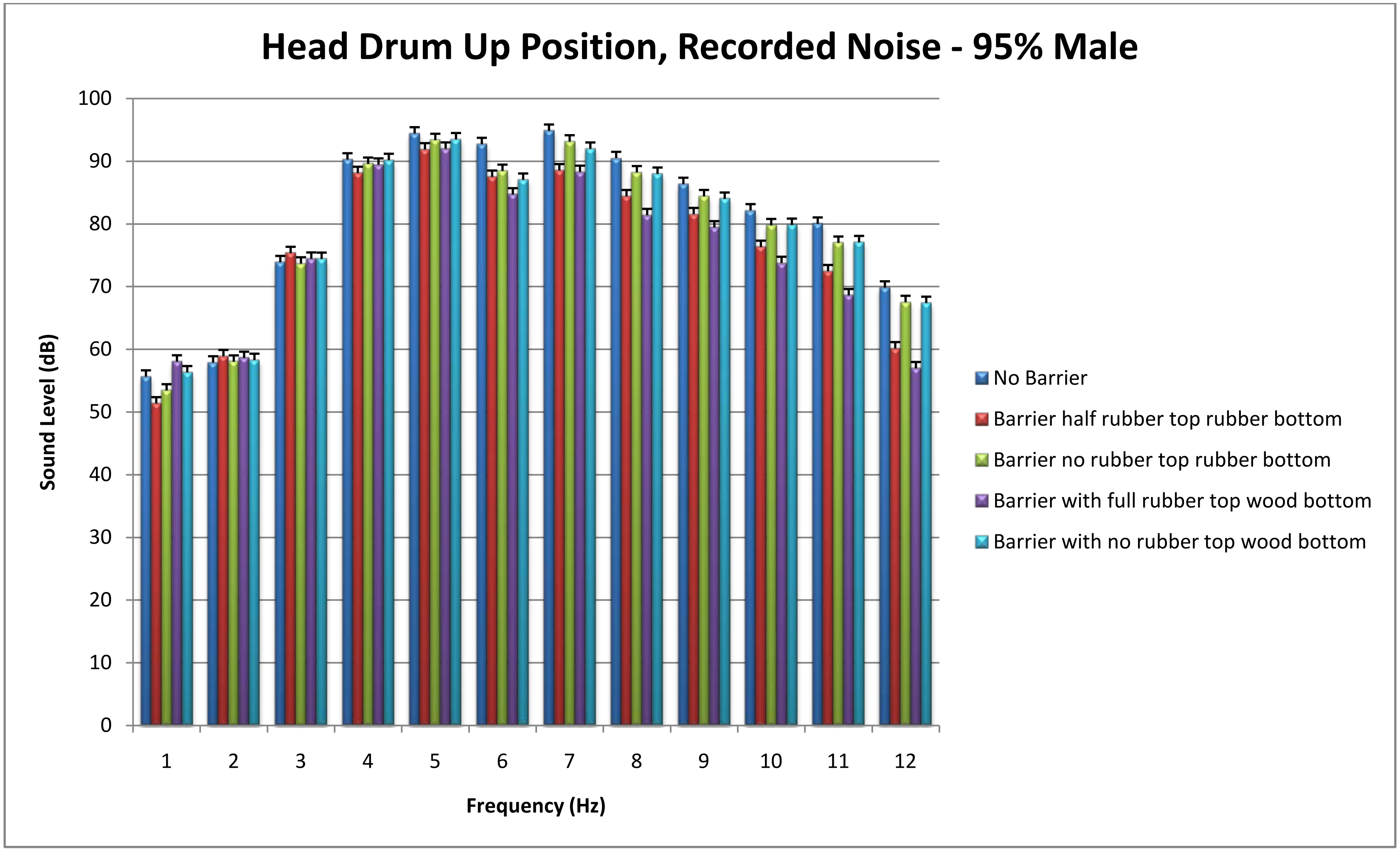


Figure B 9: Octave band analysis headgate drum, recorded noise - 95% male

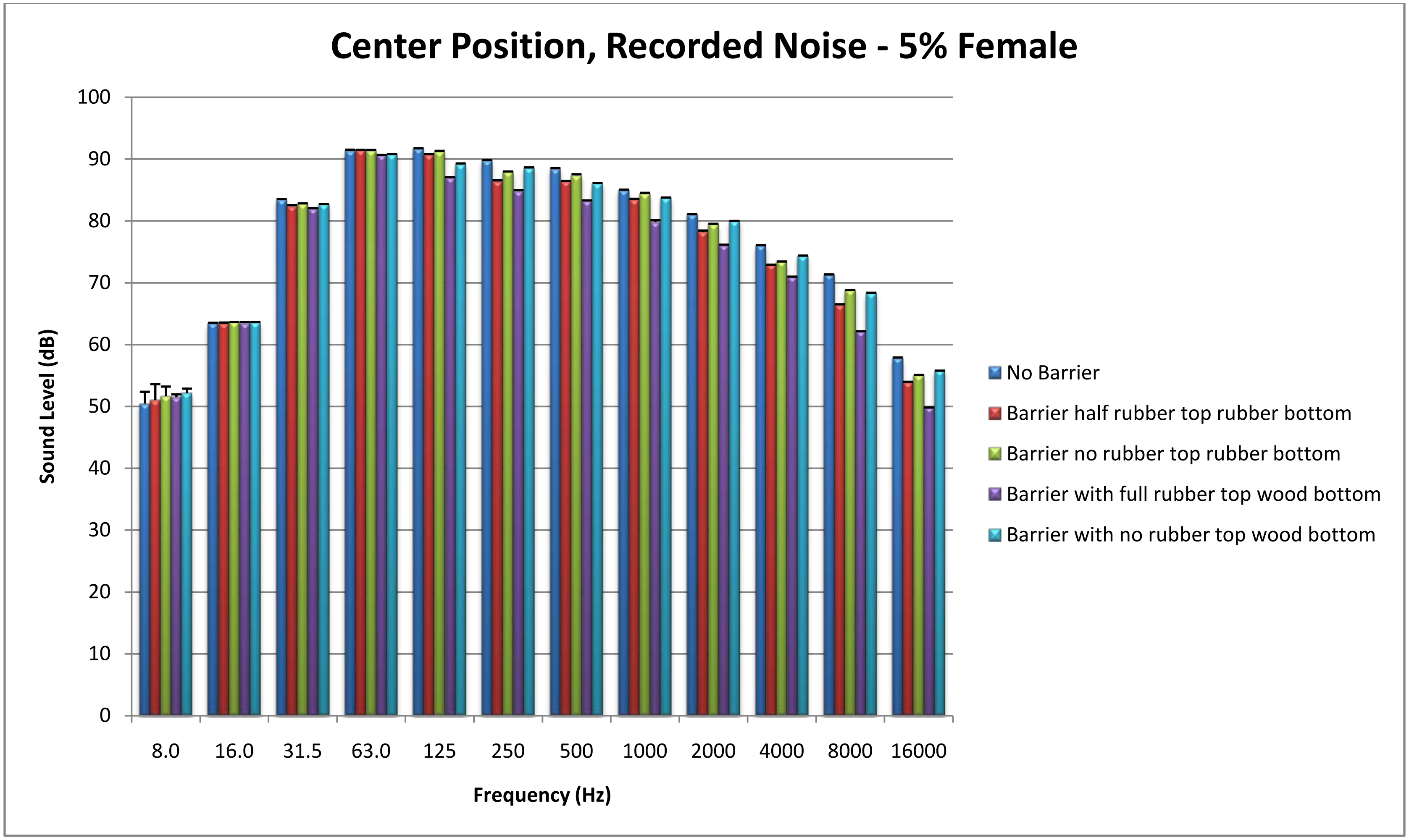


Figure B 10: Octave band analysis center position, recorded noise - 5% female

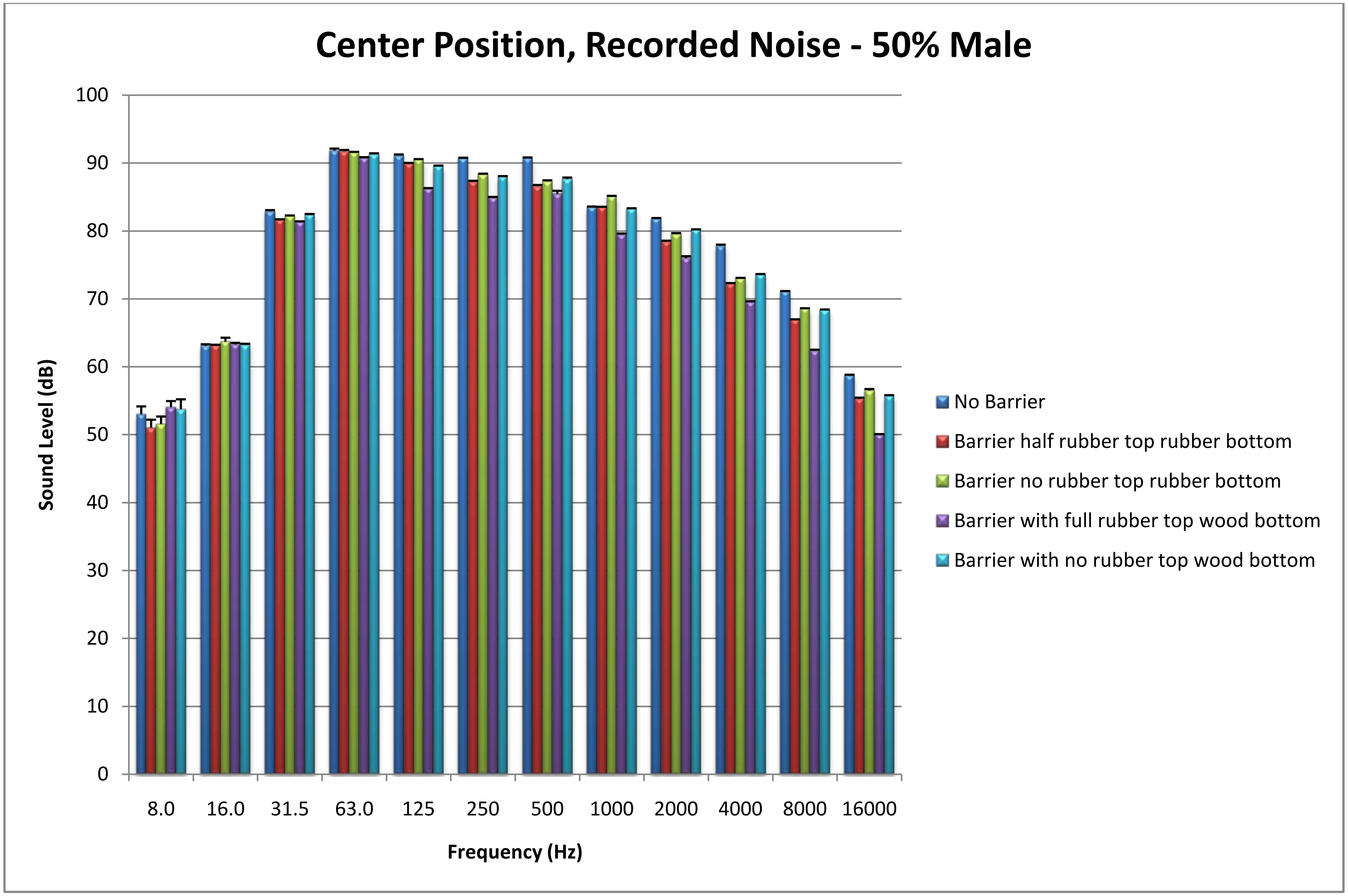


Figure B 11: Octave band analysis center position, recorded noise - 50% male

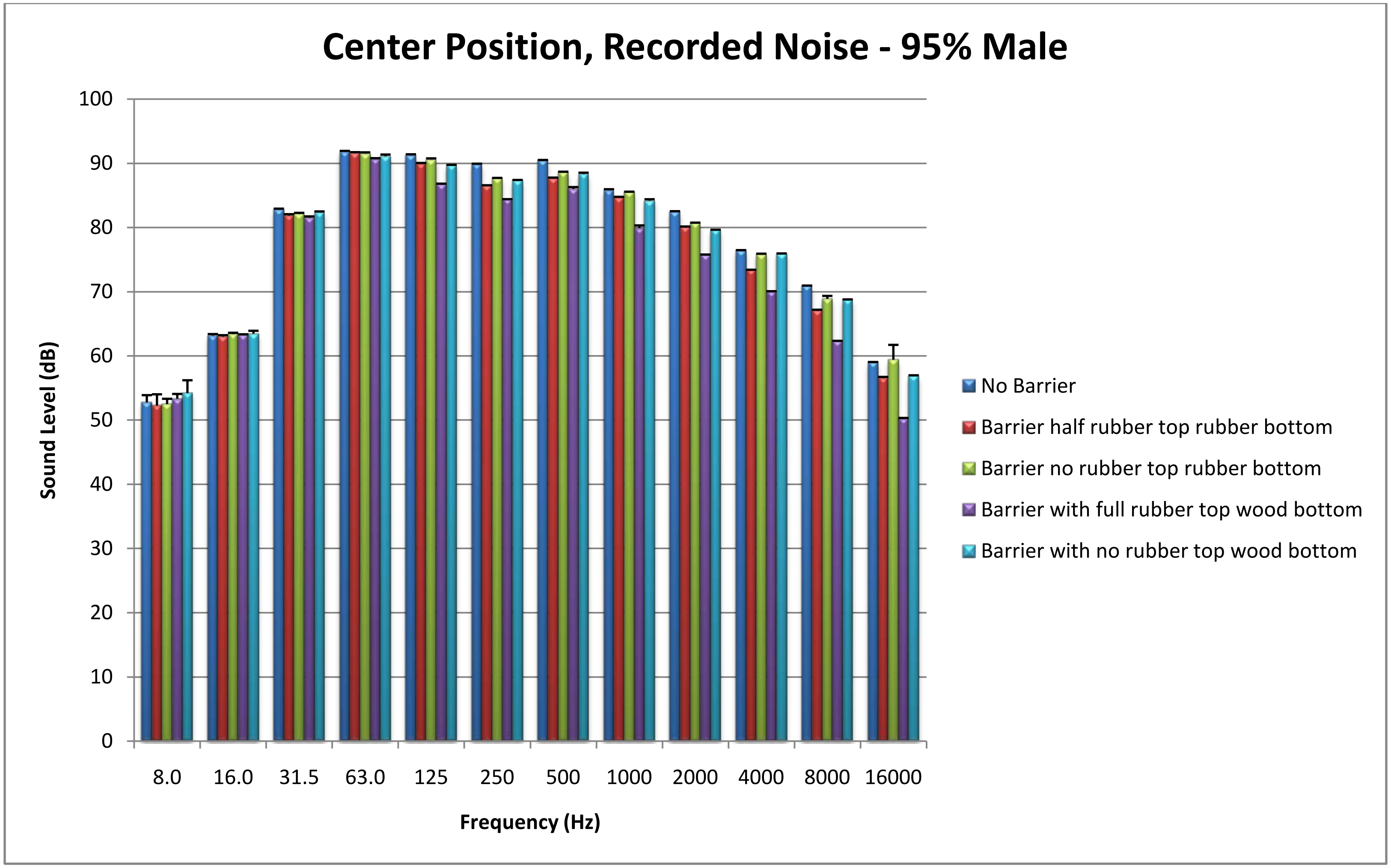


Figure B 12: Octave band analysis center position, recorded noise - 95% male

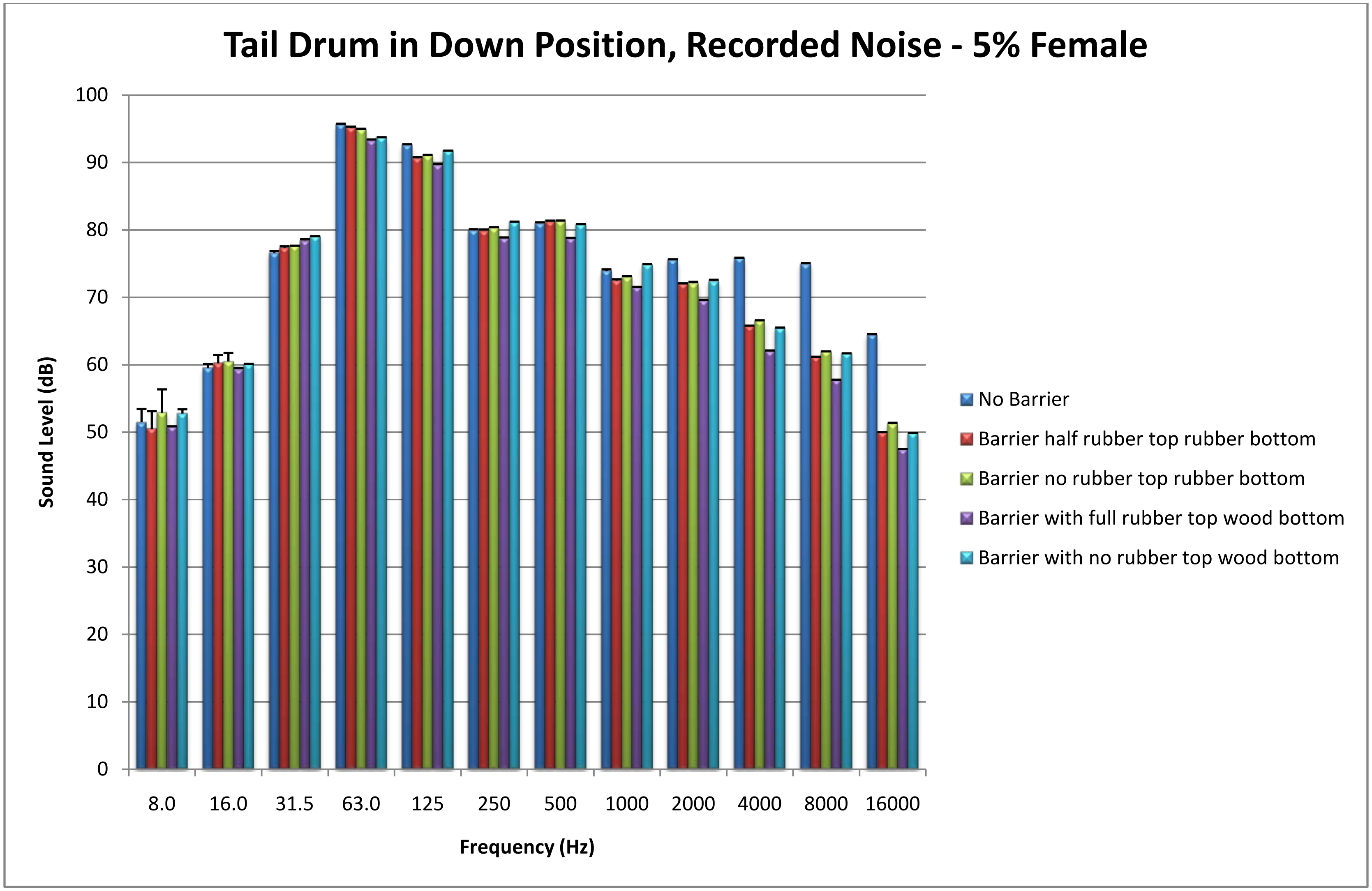


Figure B 13: Octave band analysis tailgate position, recorded noise - 5% female

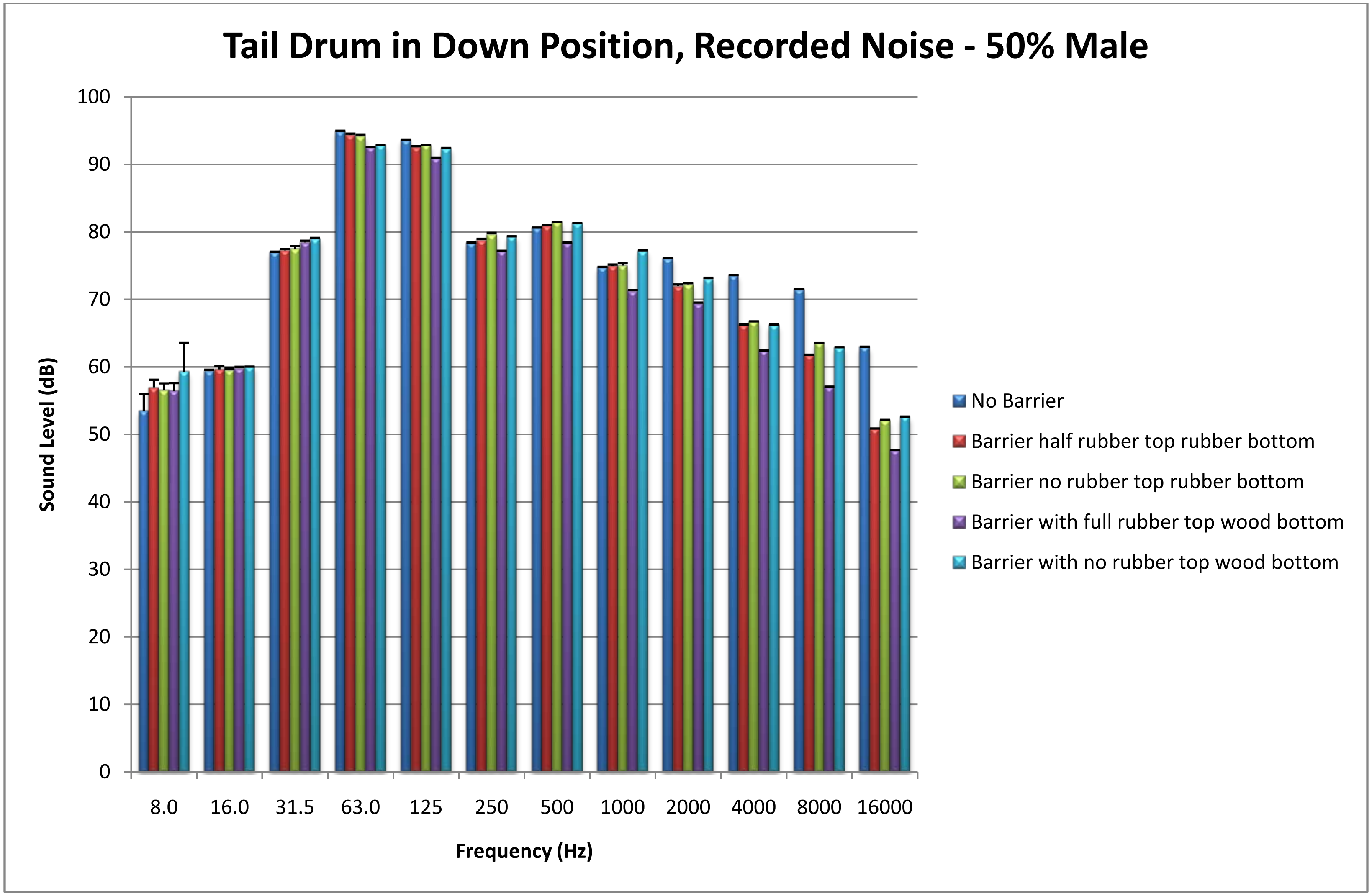


Figure B 14: Octave band analysis tailgate position, recorded noise - 50% male

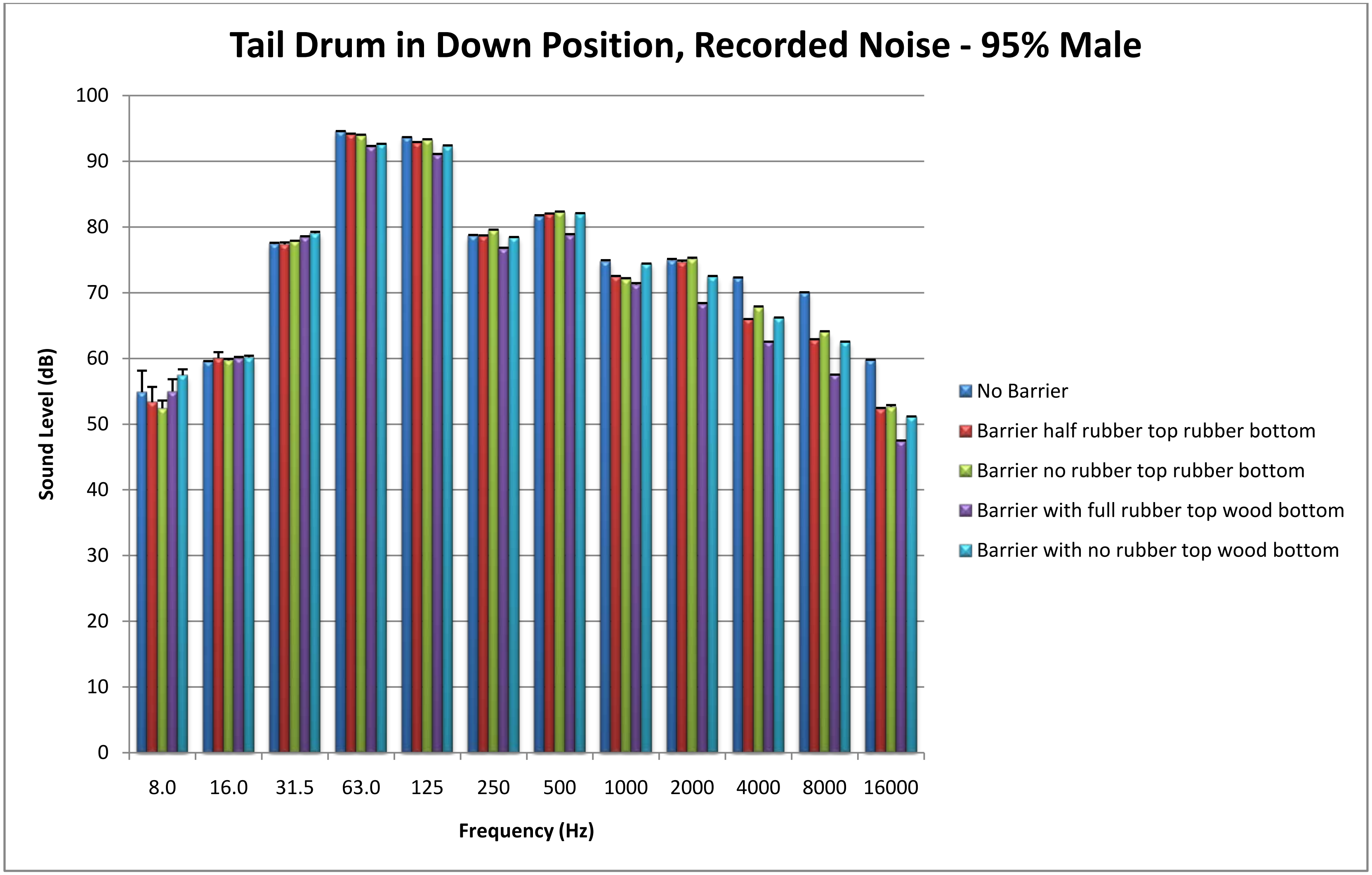


Figure B 15: Octave band analysis tailgate position, recorded noise - 95% male

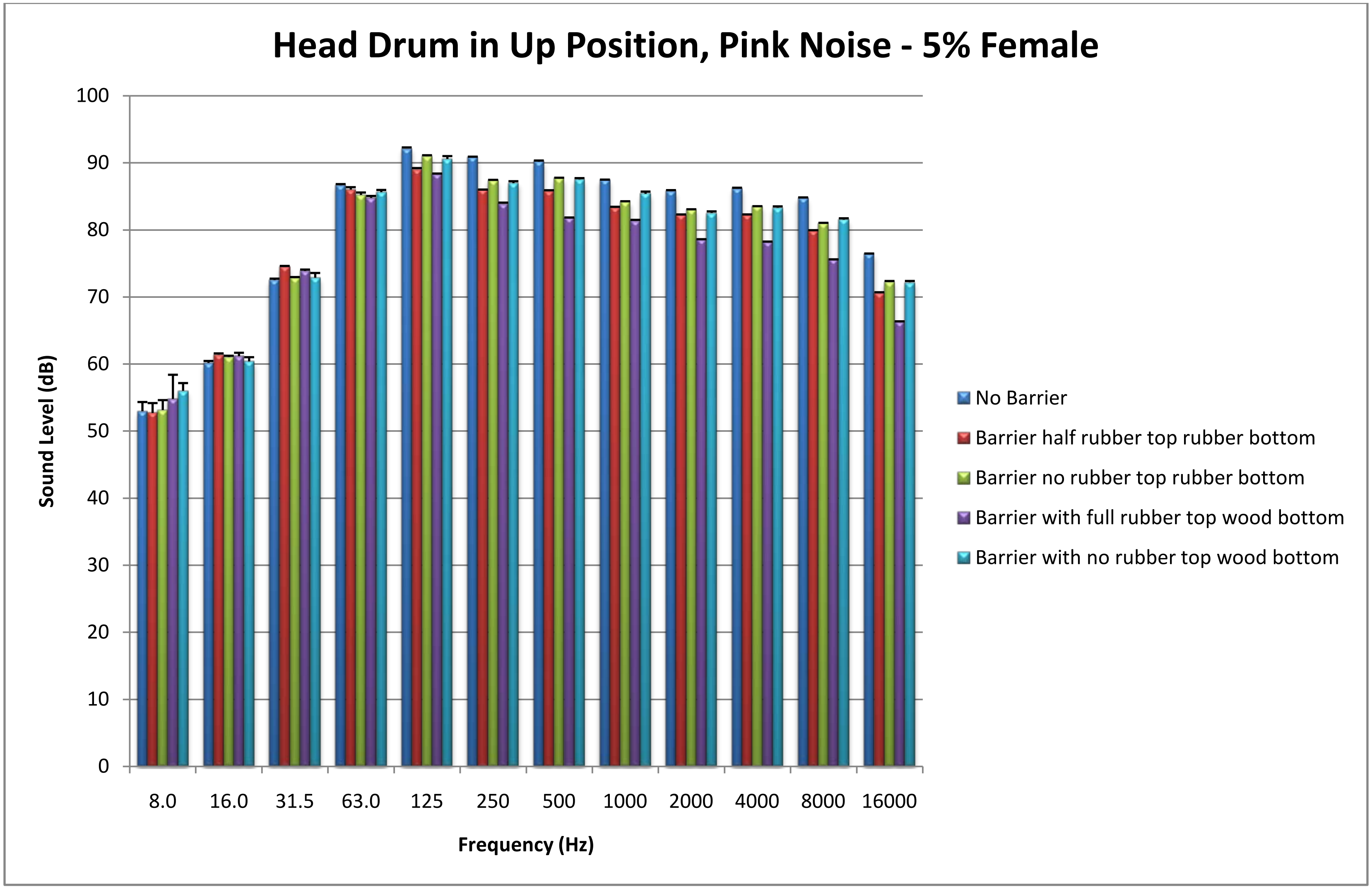


Figure B 16: Octave band analysis headgate position, pink noise - 5% female

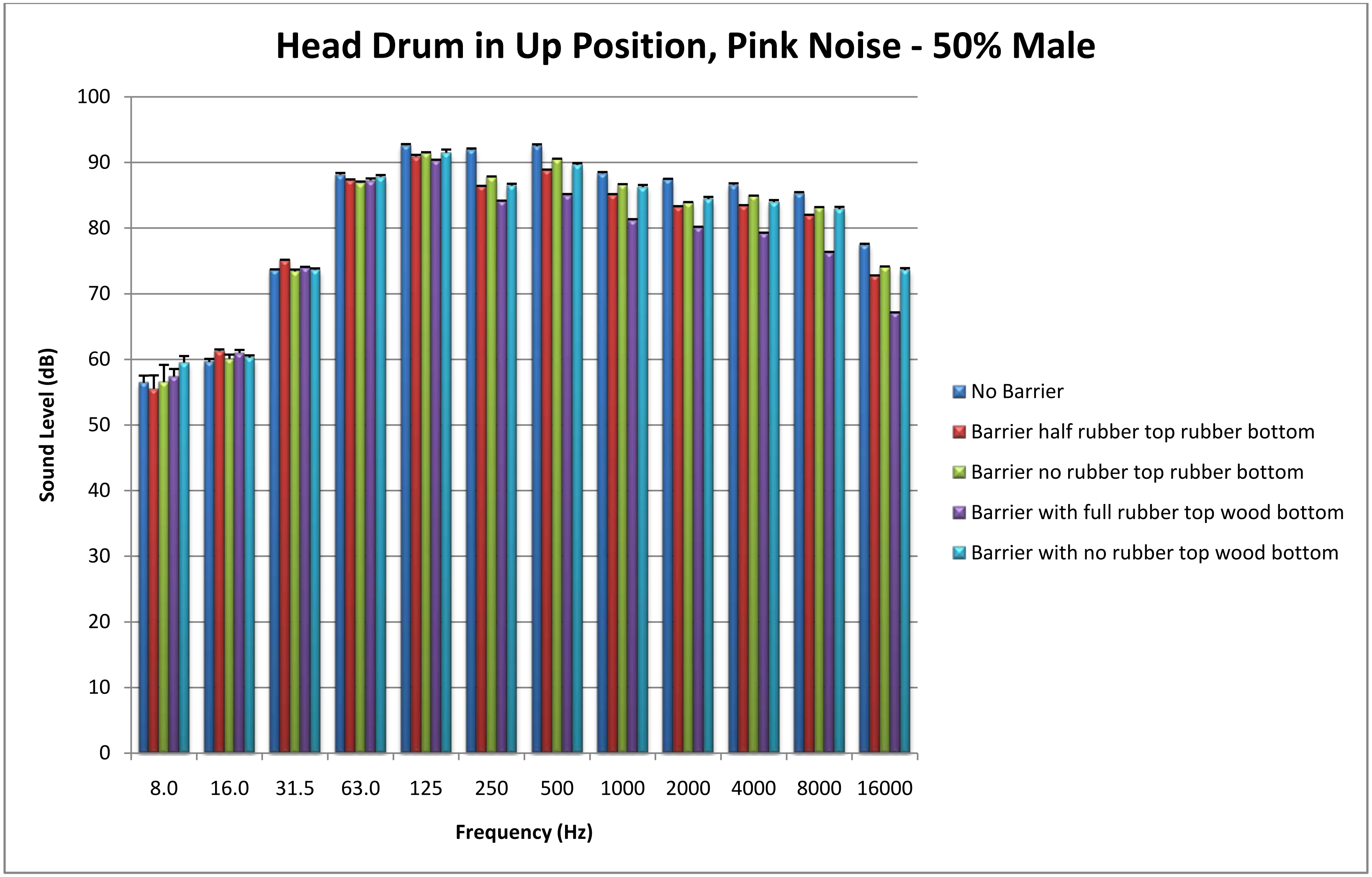


Figure B 17: Octave band analysis headgate position, pink noise - 95% male

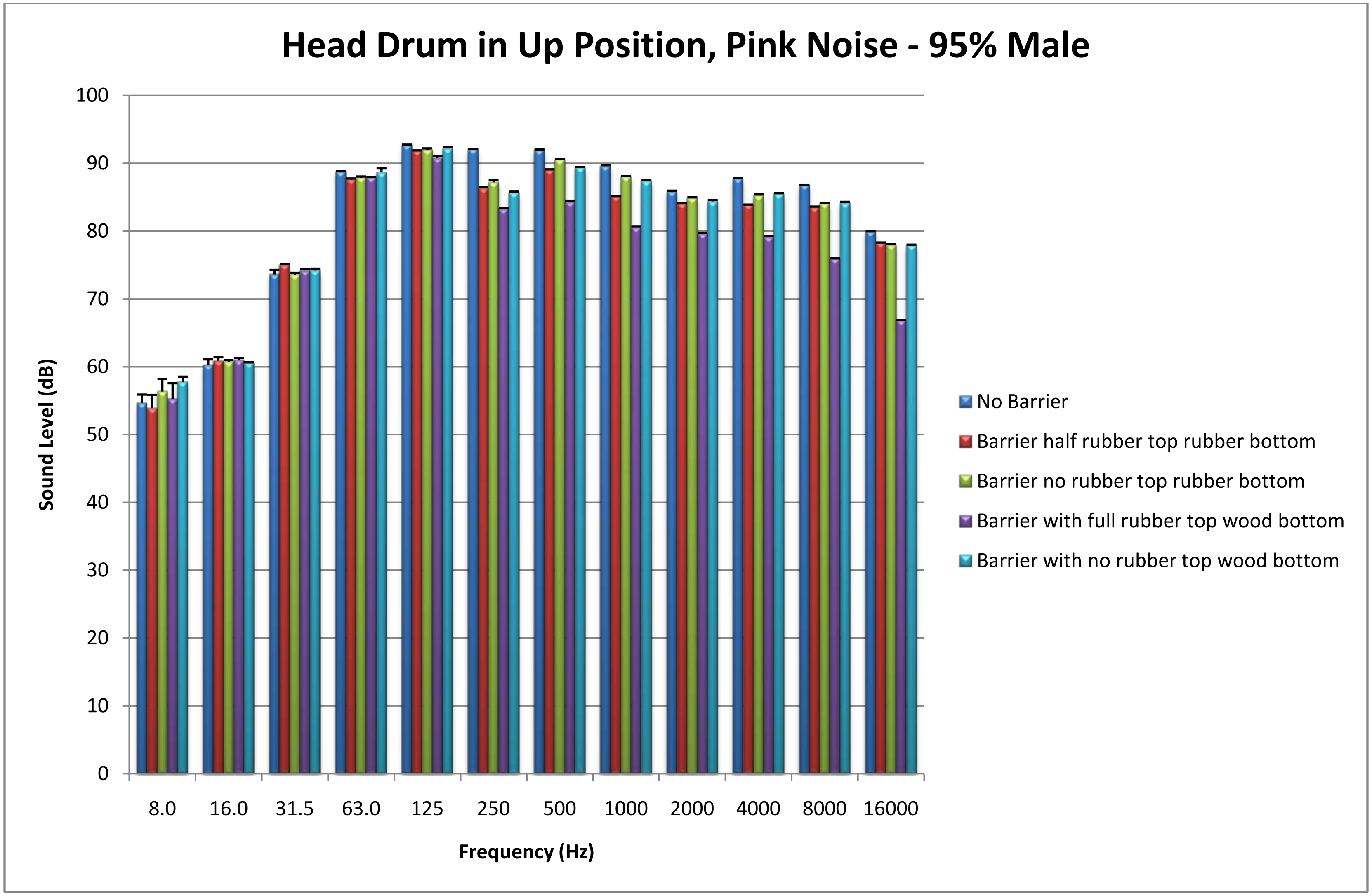


Figure B 18: Octave band analysis headgate position, pink noise - 95% male

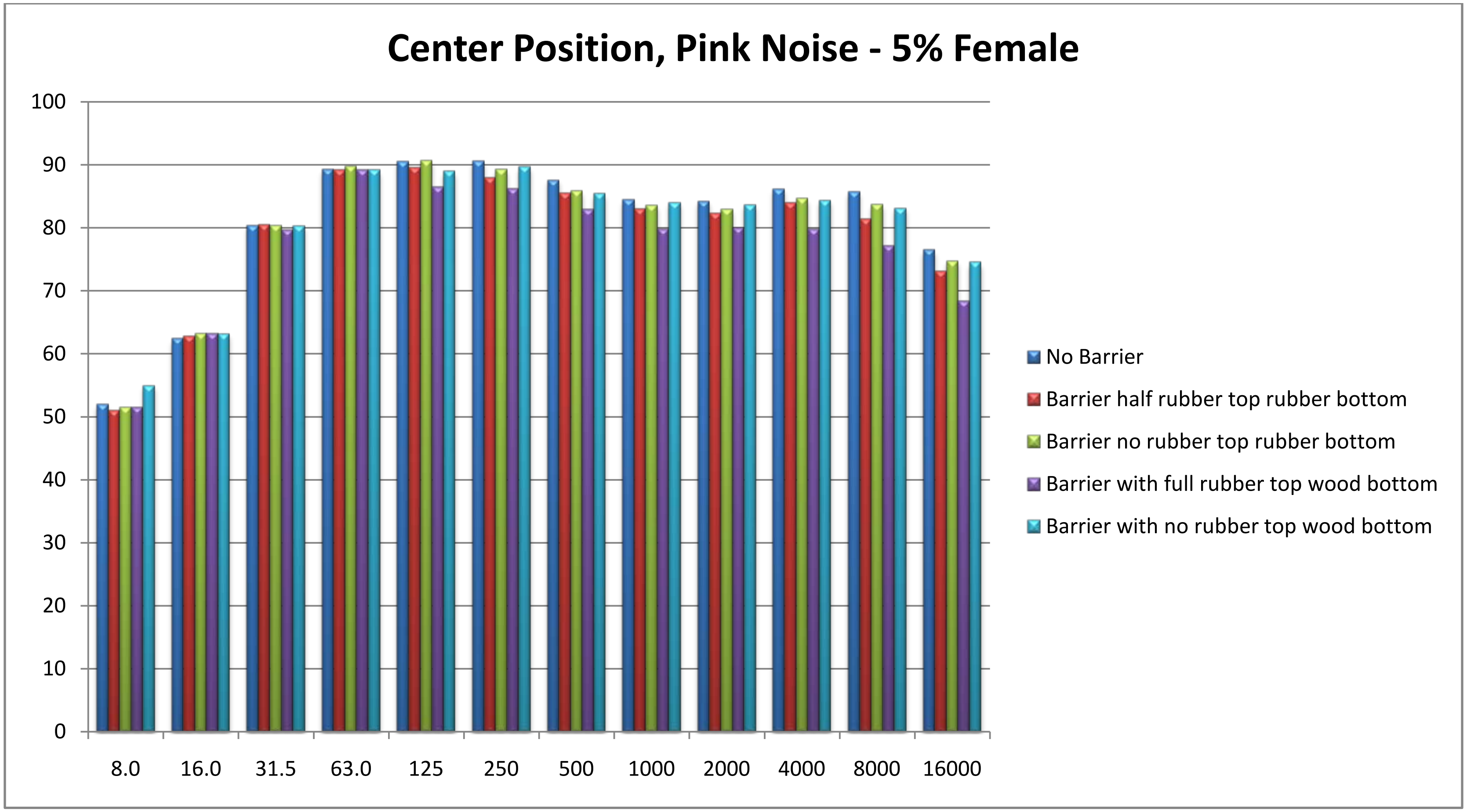


Figure B 19: Octave band analysis center position, pink noise - 5% female

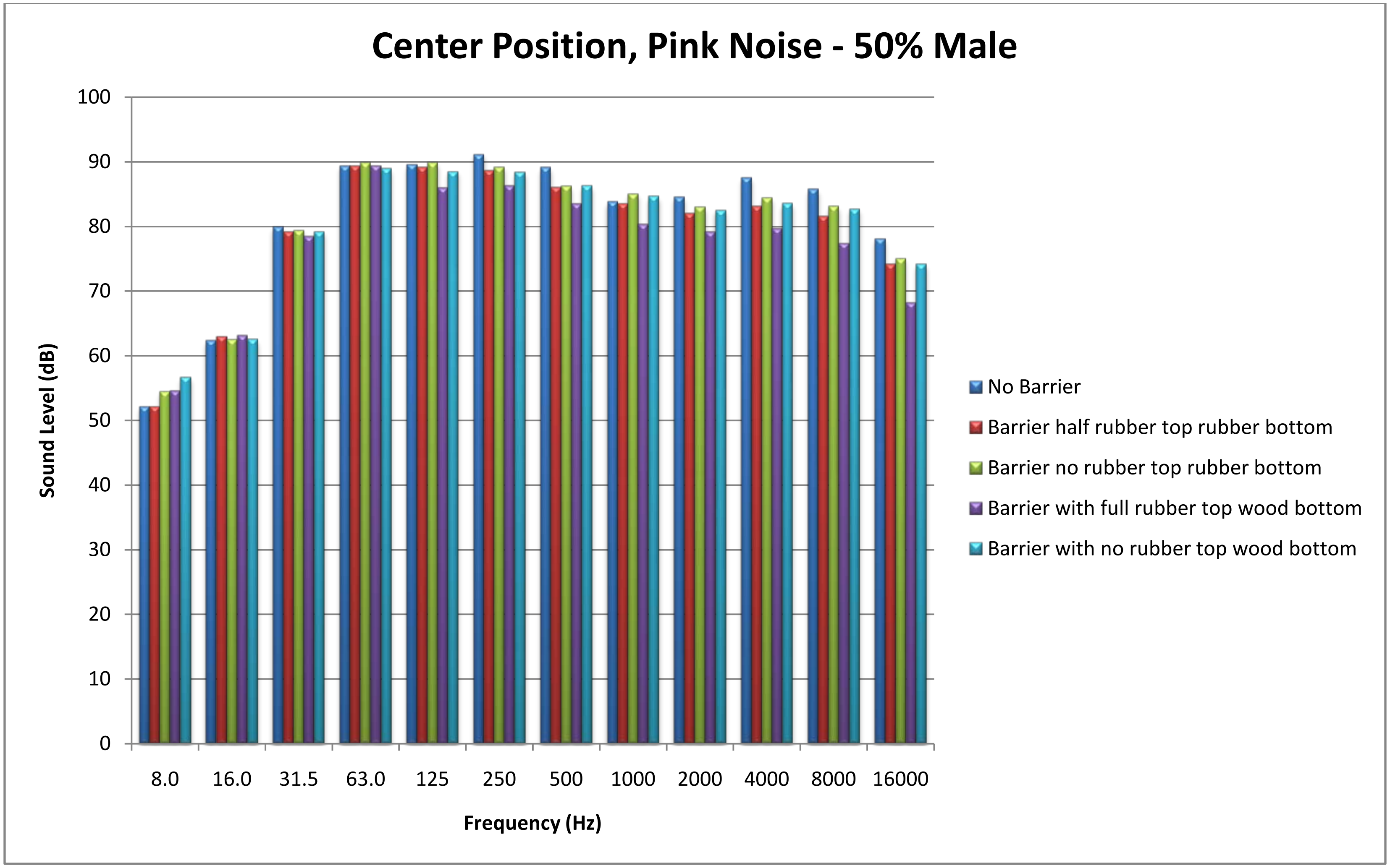


Figure B 20: Octave band analysis center position, pink noise - 50% male

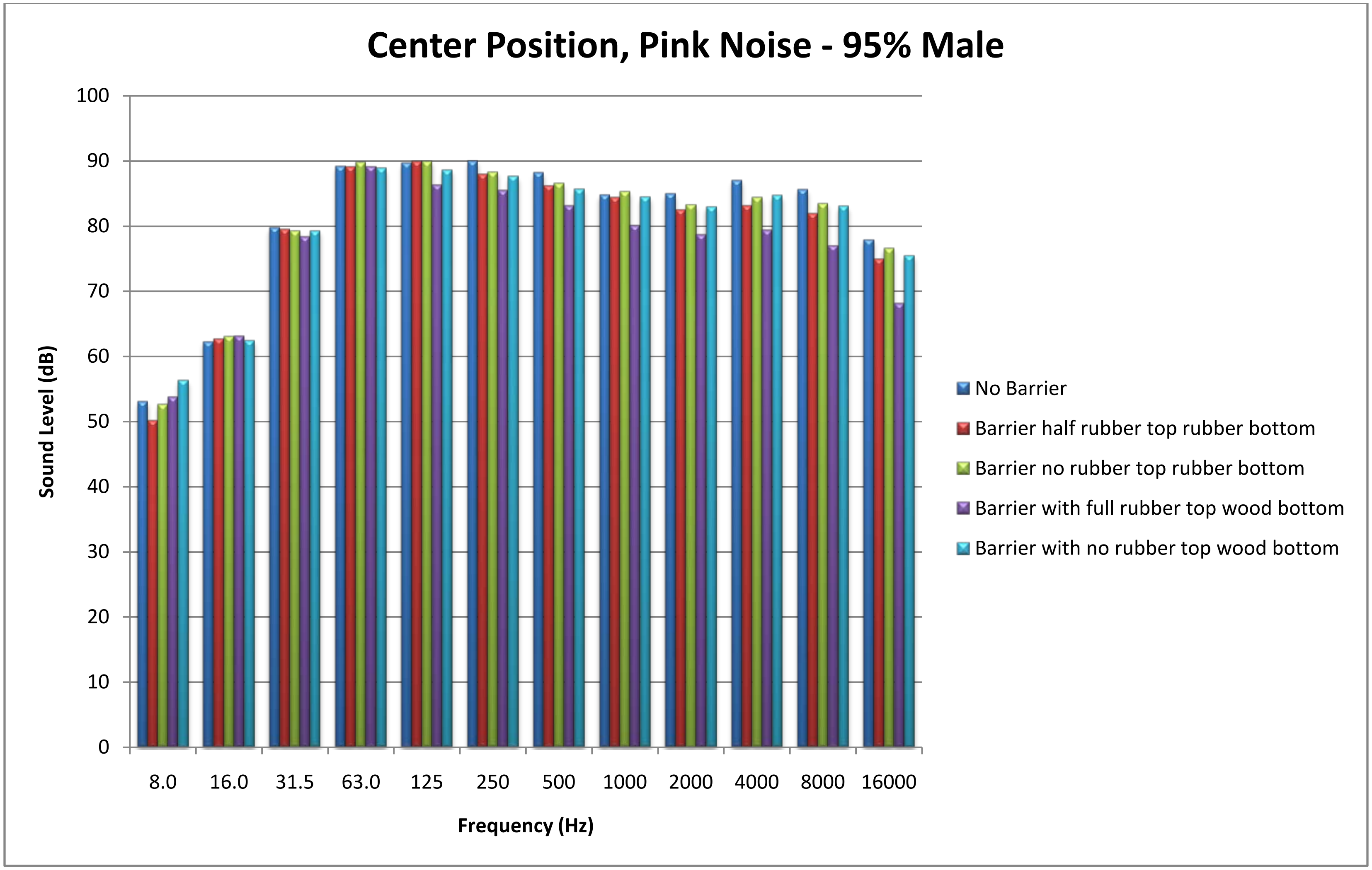


Figure B 21: Octave band analysis center position, pink noise - 95% male

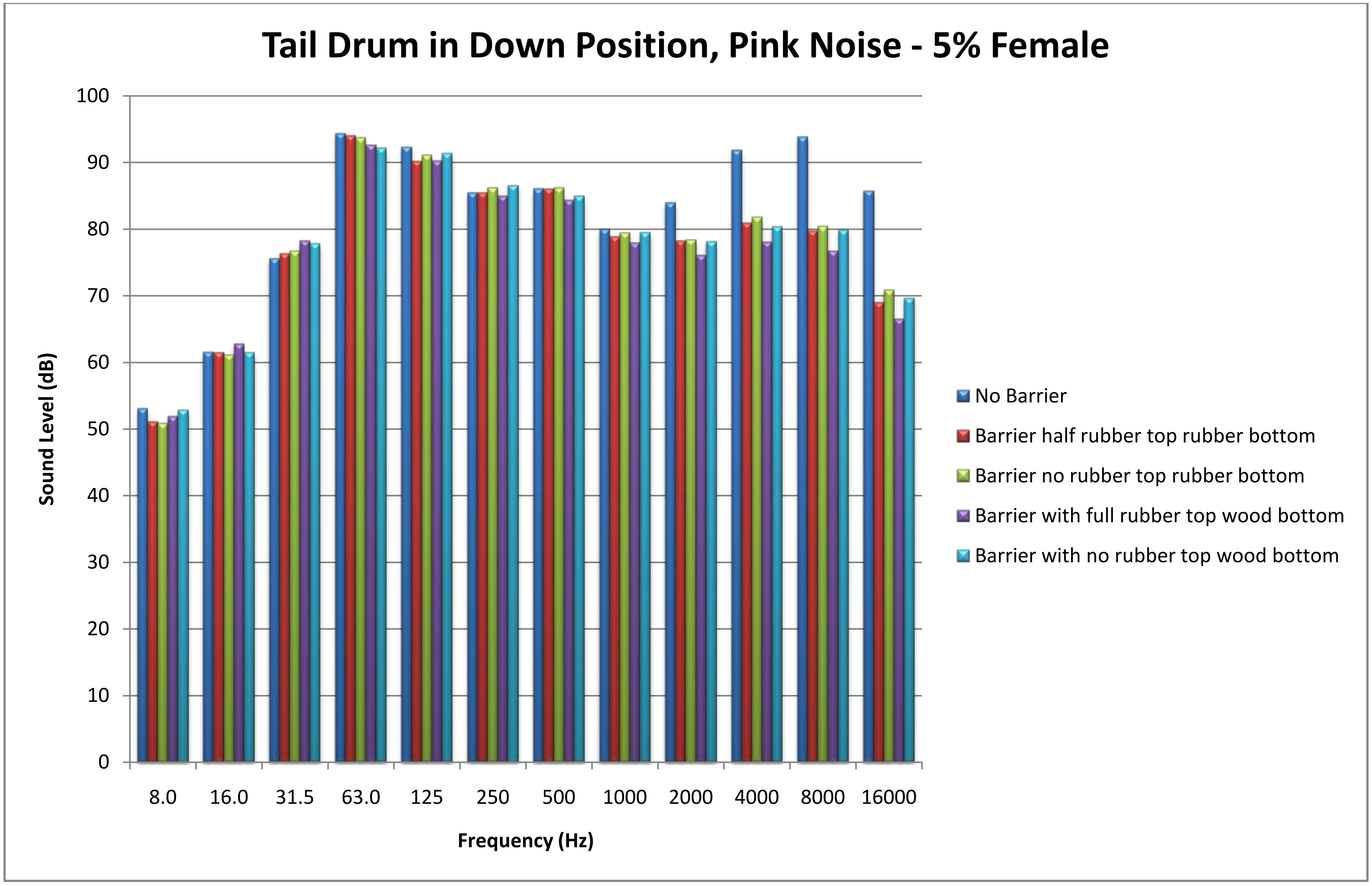


Figure B 22: Octave band analysis tailgate position, pink noise - 5% female

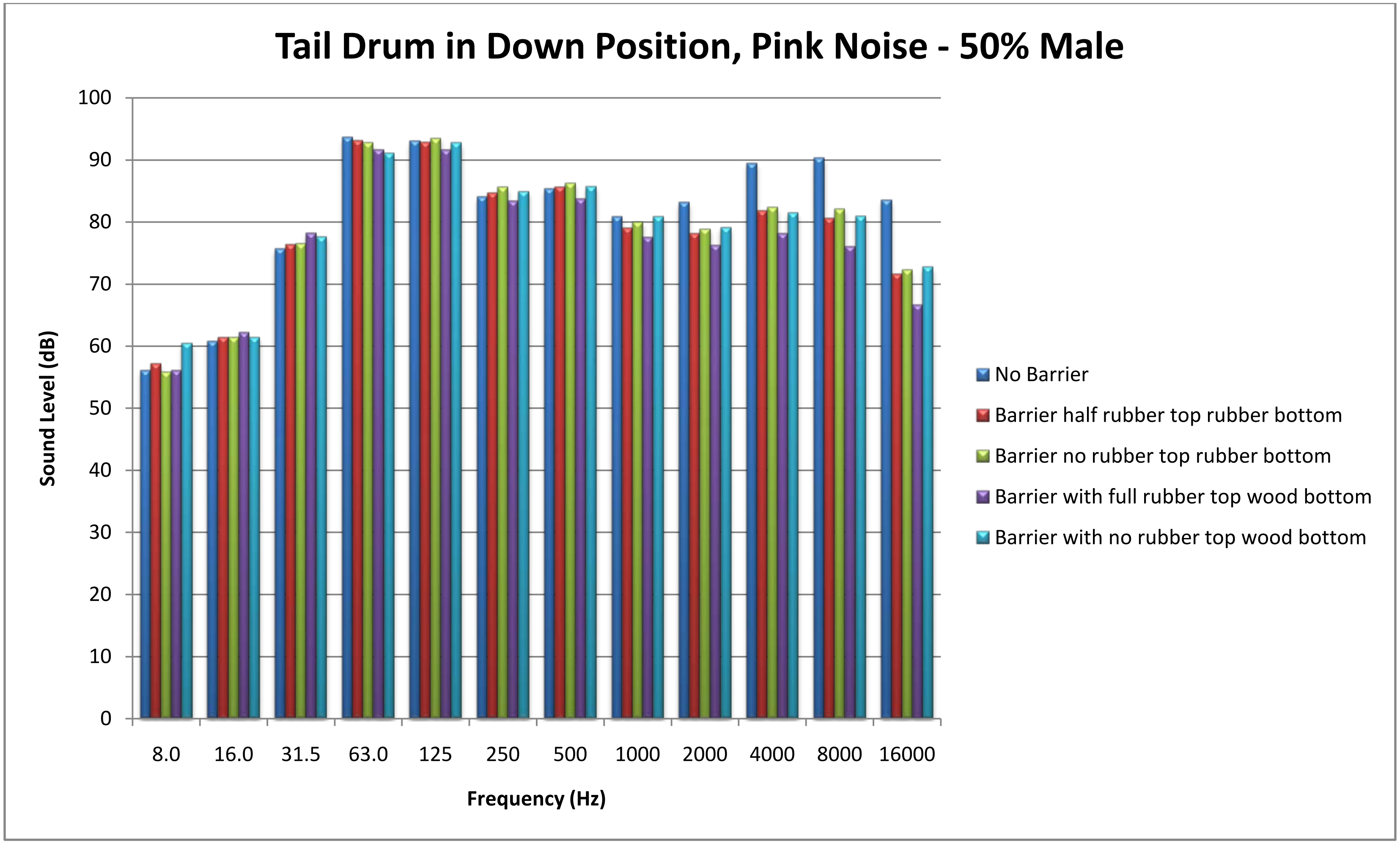


Figure B 23: Octave band analysis tailgate position, pink noise - 50% male

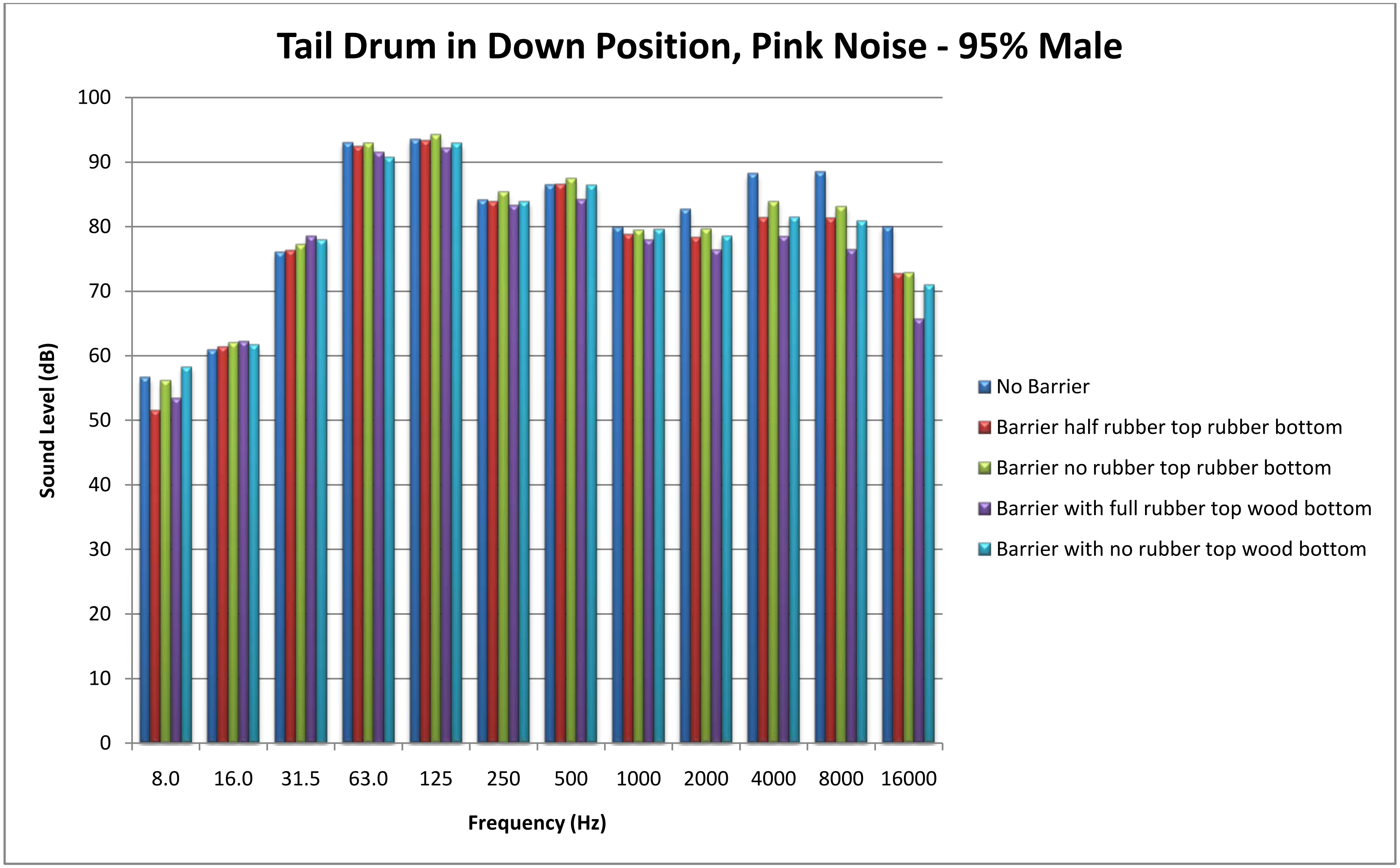


Figure B 24: Octave band analysis tailgate position, pink noise - 95% male

Appendix C

Table C 1: Barrier test at WPAFB test facility headgate position

	No Barrier	Barrier
Mean	103.06667	92.766667
Variance	0.0933333	0.0033333
Observations	3	3
Pooled Variance	0.0483333	
Hypothesized Mean Difference	0	
df	4	
t Stat	57.379859	
P(T<=t) one-tail	2.762E-07	
t Critical one-tail	2.1318468	
P(T<=t) two-tail	5.524E-07	
t Critical two-tail	2.7764451	

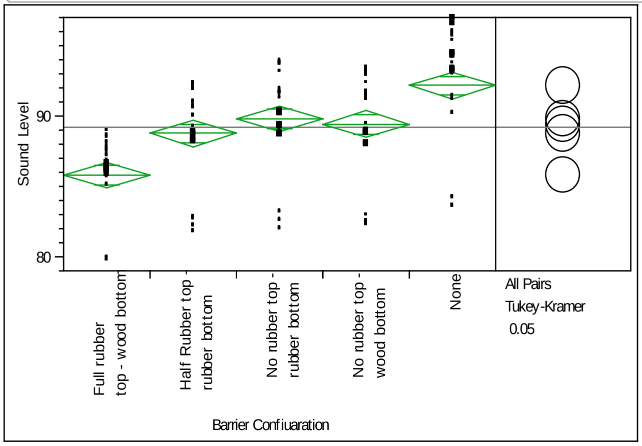
t-Test: two-sample assuming equal variances

Table C 2: Barrier test at WPAFB test facility tailgate position

	No Barrier	Barrier
Mean	100.2666667	87.16666667
Variance	0.093333333	0.013333333
Observations	3	3
Pooled Variance	0.053333333	
Hypothesized Mean Difference	0	
df	4	
t Stat	69.47324125	
P(T<=t) one-tail	1.28603E-07	
t Critical one-tail	2.131846782	
P(T<=t) two-tail	2.57206E-07	
t Critical two-tail	2.776445105	

t-Test: Two-Sample Assuming Equal Variances

Oneway Analysis of Sound Level By Barrier Confiuaration



Oneway Anova

Summary of Fit

Rsquare	0.256043
Adj Rsquare	0.244814
Root Mean Square Error	3.524213
Mean of Response	89.18444
Observations (or Sum Wgts)	270

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Barrier Confiuaration	4	1132.7539	283.188	22.8009	<.0001 *
Error	265	3291.3207	12.420		
C. Total	269	4424.0747			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Full rubber top - wood bottom	54	85.7963	0.47958	84.852	86.741
Half Rubber top - rubber bottom	54	88.7500	0.47958	87.806	89.694
No rubber top - rubber bottom	54	89.7944	0.47958	88.850	90.739
No rubber top - wood bottom	54	89.4167	0.47958	88.472	90.361
None	54	92.1648	0.47958	91.221	93.109

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
2.74666	0.05

Abs(Dif)-LSD

	None	No rubber top - rubber bottom	No rubber top - wood bottom	Half Rubber top - rubber bottom	Full rubber top - wood bottom
None	-1.8629	0.5075	0.8853	1.5519	4.5056
No rubber top - rubber bottom	0.5075	-1.8629	-1.4851	-0.8184	2.1353
No rubber top - wood bottom	0.8853	-1.4851	-1.8629	-1.1962	1.7575
Half Rubber top - rubber bottom	1.5519	-0.8184	-1.1962	-1.8629	1.0908
Full rubber top - wood bottom	4.5056	2.1353	1.7575	1.0908	-1.8629

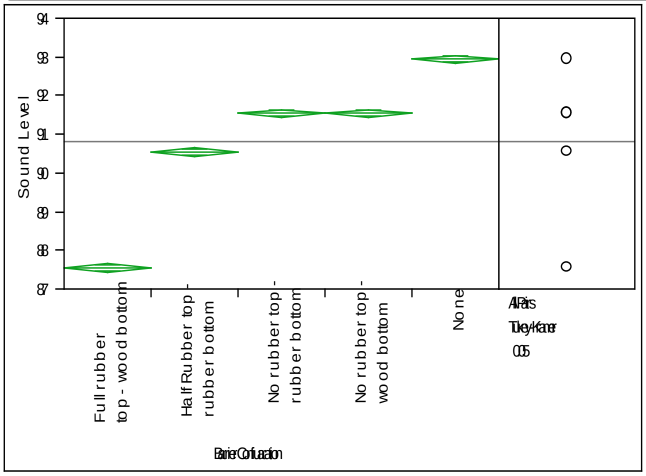
Positive values show pairs of means that are significantly different.

Level				Mean
None	A			92.164815
No rubber top - rubber bottom		B		89.794444
No rubber top - wood bottom		B		89.416667
Half Rubber top - rubber bottom		B		88.750000
Full rubber top - wood bottom			C	85.796296

Levels not connected by same letter are significantly different.

Figure C 1: Oneway analysis of sound level by barrier configuration

Oneway Analysis of Sound Level By Barrier Configuration



Oneway Anova

Summary of Fit

Rsquare	0.998509
Adj Rsquare	0.997912
Root Mean Square Error	0.085635
Mean of Response	90.81333
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F	
Barrier Configuration	4	49.10400	12.2760	1674.000	<.0001	*
Error	10	0.07333	0.0073			
C Total	14	49.17733				

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Full rubber top-wood bottom	3	87.5333	0.04944	87.423	87.643
Half Rubber top-rubber bottom	3	90.5333	0.04944	90.423	90.643
No rubber top-rubber bottom	3	91.5333	0.04944	91.423	91.643
No rubber top-wood bottom	3	91.5333	0.04944	91.423	91.643
None	3	92.9333	0.04944	92.823	93.043

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
3.29108	0.05

Abs(Dif)-LSD

	None	No rubber top-wood bottom	No rubber top-rubber bottom	Half Rubber top-rubber bottom	Full rubber top-wood bottom
None	-0.2301	1.1699	1.1699	2.1699	5.1699
No rubber top-wood bottom	1.1699	-0.2301	-0.2301	0.7699	3.7699
No rubber top-rubber bottom	1.1699	-0.2301	-0.2301	0.7699	3.7699
Half Rubber top-rubber bottom	2.1699	0.7699	0.7699	-0.2301	2.7699
Full rubber top-wood bottom	5.1699	3.7699	3.7699	2.7699	-0.2301

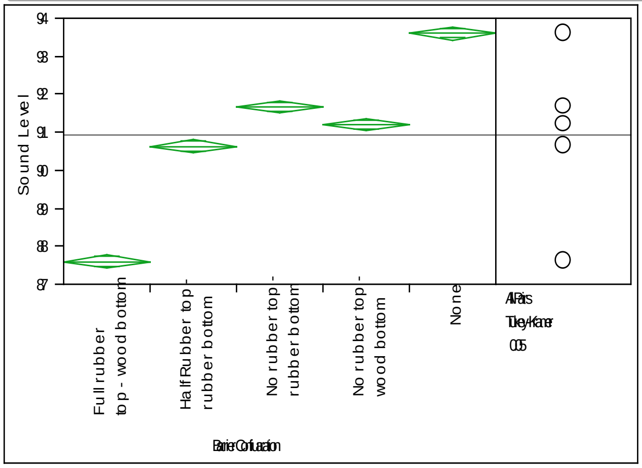
Positive values show pairs of means that are significantly different.

Level		Mean
None	A	92.933333
No rubber top-wood bottom	B	91.533333
No rubber top-rubber bottom	B	91.533333
Half Rubber top-rubber bottom	C	90.533333
Full rubber top-wood bottom	D	87.533333

Levels not connected by same letter are significantly different.

Figure C 2: Oneway analysis of sound level by barrier configuration sound type=pink, position=center, operator height=low

Oneway Analysis of Sound Level By Barrier Configuration



Oneway Anova

Summary of Fit

Rsquare	0.996956
Adj Rsquare	0.995738
Root Mean Square Error	0.131656
Mean of Response	90.94
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F	
Barrier Configuration	4	56.762667	14.1907	818.6923	<.0001	*
Error	10	0.173333	0.0173			
C Total	14	56.936000				

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Full rubber top - wood bottom	3	87.6000	0.07601	87.431	87.769
Half Rubber top - rubber bottom	3	90.6333	0.07601	90.464	90.803
No rubber top - rubber bottom	3	91.6667	0.07601	91.497	91.836
No rubber top - wood bottom	3	91.2000	0.07601	91.031	91.369
None	3	93.6000	0.07601	93.431	93.769

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
3.29108	0.05

Abs(Dif)-LSD

	None	No rubber top - rubber bottom	No rubber top - wood bottom	Half Rubber top - rubber bottom	Full rubber top - wood bottom
None	-0.3538	1.5796	2.0462	2.6129	5.6462
No rubber top - rubber bottom	1.5796	-0.3538	0.1129	0.6796	3.7129
No rubber top - wood bottom	2.0462	0.1129	-0.3538	0.2129	3.2462
Half Rubber top - rubber bottom	2.6129	0.6796	0.2129	-0.3538	2.6796
Full rubber top - wood bottom	5.6462	3.7129	3.2462	2.6796	-0.3538

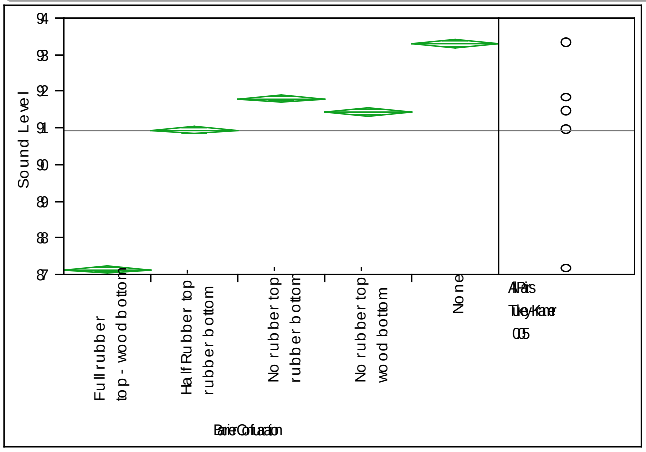
Positive values show pairs of means that are significantly different.

Level		Mean
None	A	93.600000
No rubber top - rubber bottom	B	91.666667
No rubber top - wood bottom	C	91.200000
Half Rubber top - rubber bottom	D	90.633333
Full rubber top - wood bottom	E	87.600000

Levels not connected by same letter are significantly different.

Figure C 3: Oneway analysis of sound level by barrier configuration sound type=pink, position=center, operator height=medium

Oneway Analysis of Sound Level By Barrier Configuration



Oneway Anova

Summary of Fit

Rsquare	09995
Adj Rsquare	099671
Root Mean Square Error	00746
Mean of Response	9092
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	
Barrier Configuration	4	6312400	15781 0	2630167	<0001	*
Error	10	0060000	00060			
C Total	14	6318400				

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Full rubber top-wood bottom	3	871333	004472	87034	87233
Half Rubber top-rubber bottom	3	909333	004472	90834	91033
No rubber top-rubber bottom	3	918000	004472	91700	91900
No rubber top-wood bottom	3	914333	004472	91334	91533
None	3	933000	004472	93200	93400

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
329108	005

Abs(Dif)-LSD

	None	No rubber top-rubber bottom	No rubber top-wood bottom	Half Rubber top-rubber bottom	Full rubber top-wood bottom
None	-02081	12919	16585	21585	59585
No rubber top-rubber bottom	12919	-02081	01585	06585	44585
No rubber top-wood bottom	16585	01585	-02081	02919	40919
Half Rubber top-rubber bottom	21585	06585	02919	-02081	35919
Full rubber top-wood bottom	59585	44585	40919	35919	-02081

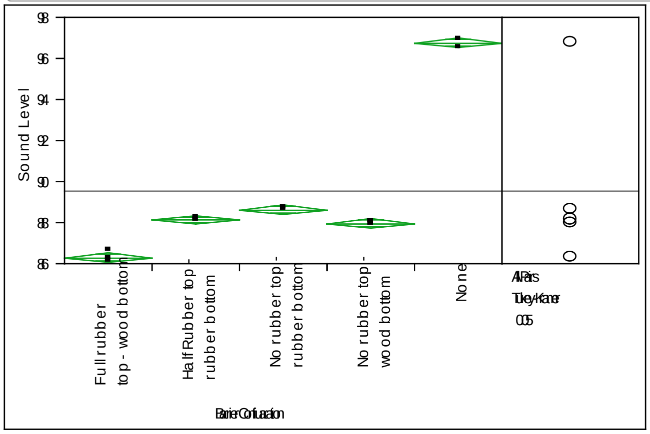
Positive values show pairs of means that are significantly different.

Level		Mean
None	A	93300000
No rubber top-rubber bottom	B	91800000
No rubber top-wood bottom	C	91433333
Half Rubber top-rubber bottom	D	90933333
Full rubber top-wood bottom	E	87133333

Levels not connected by same letter are significantly different.

Figure C 4: Oneway analysis of sound level by barrier configuration sound type=pink, position=center, operator height=high

Oneway Analysis of Sound Level By Barrier Configuration



Oneway Anova

Summary of Fit

Rsquare	0.998694
Adj Rsquare	0.998172
Root Mean Square Error	0.163299
Mean of Response	89.56
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F	
Barrier Configuration	4	203.98933	50.9973	1912.400	<.0001	*
Error	10	0.26667	0.0267			
C Total	14	204.25600				

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Full rubber top - wood bottom	3	86.3000	0.09428	86.090	86.510
Half Rubber top - rubber bottom	3	88.1333	0.09428	87.923	88.343
No rubber top - rubber bottom	3	88.6333	0.09428	88.423	88.843
No rubber top - wood bottom	3	87.9667	0.09428	87.757	88.177
None	3	96.7667	0.09428	96.557	96.977

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
3.29108	0.05

Abs(Dif)-LSD

	None	No rubber top - rubber bottom	Half Rubber top - rubber bottom	No rubber top - wood bottom	Full rubber top - wood bottom
None	-0.439	7.695	8.195	8.361	10.028
No rubber top - rubber bottom	7.695	-0.439	0.061	0.228	1.895
Half Rubber top - rubber bottom	8.195	0.061	-0.439	-0.272	1.395
No rubber top - wood bottom	8.361	0.228	-0.272	-0.439	1.228
Full rubber top - wood bottom	10.028	1.895	1.395	1.228	-0.439

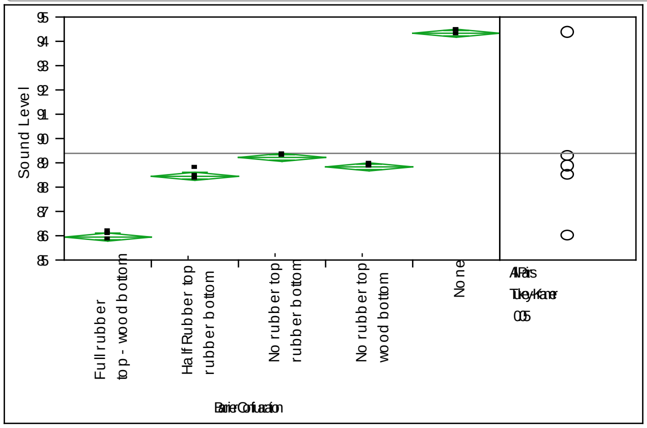
Positive values show pairs of means that are significantly different.

Level					Mean
None	A				96.766667
No rubber top - rubber bottom		B			88.633333
Half Rubber top - rubber bottom			C		88.133333
No rubber top - wood bottom			C		87.966667
Full rubber top - wood bottom				D	86.300000

Levels not connected by same letter are significantly different.

Figure C 5: Oneway analysis of sound level by barrier configuration sound type=pink, position=headgate, operator height=low

Oneway Analysis of Sound Level By Barrier Configuration



Oneway Anova

Summary of Fit

Rsquare	0.99845
Adj Rsquare	0.99783
Root Mean Square Error	0.131656
Mean of Response	89.36667
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F	
Barrier Configuration	4	112.02000	28.0050	1615.673	<.0001	*
Error	10	0.17333	0.0173			
C. Total	14	112.19333				

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Full rubber top-wood bottom	3	85.9667	0.07601	85.797	86.136
Half Rubber top-rubber bottom	3	88.4667	0.07601	88.297	88.636
No rubber top-rubber bottom	3	89.2333	0.07601	89.064	89.403
No rubber top-wood bottom	3	88.8333	0.07601	88.664	89.003
None	3	94.3333	0.07601	94.164	94.503

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
3.29108	0.05

Abs(Dif)-LSD

	None	No rubber top-rubber bottom	No rubber top-wood bottom	Half Rubber top-rubber bottom	Full rubber top-wood bottom
None	-0.3538	4.7462	5.1462	5.5129	8.0129
No rubber top-rubber bottom	4.7462	-0.3538	0.0462	0.4129	2.9129
No rubber top-wood bottom	5.1462	0.0462	-0.3538	0.0129	2.5129
Half Rubber top-rubber bottom	5.5129	0.4129	0.0129	-0.3538	2.1462
Full rubber top-wood bottom	8.0129	2.9129	2.5129	2.1462	-0.3538

Positive values show pairs of means that are significantly different.

Level						Mean
None	A					94.333333
No rubber top-rubber bottom		B				89.233333
No rubber top-wood bottom			C			88.833333
Half Rubber top-rubber bottom				D		88.466667
Full rubber top-wood bottom					E	85.966667

Levels not connected by same letter are significantly different.

Figure C 6: Oneway analysis of sound level by barrier configuration sound type=pink, position=headgate, operator height=medium

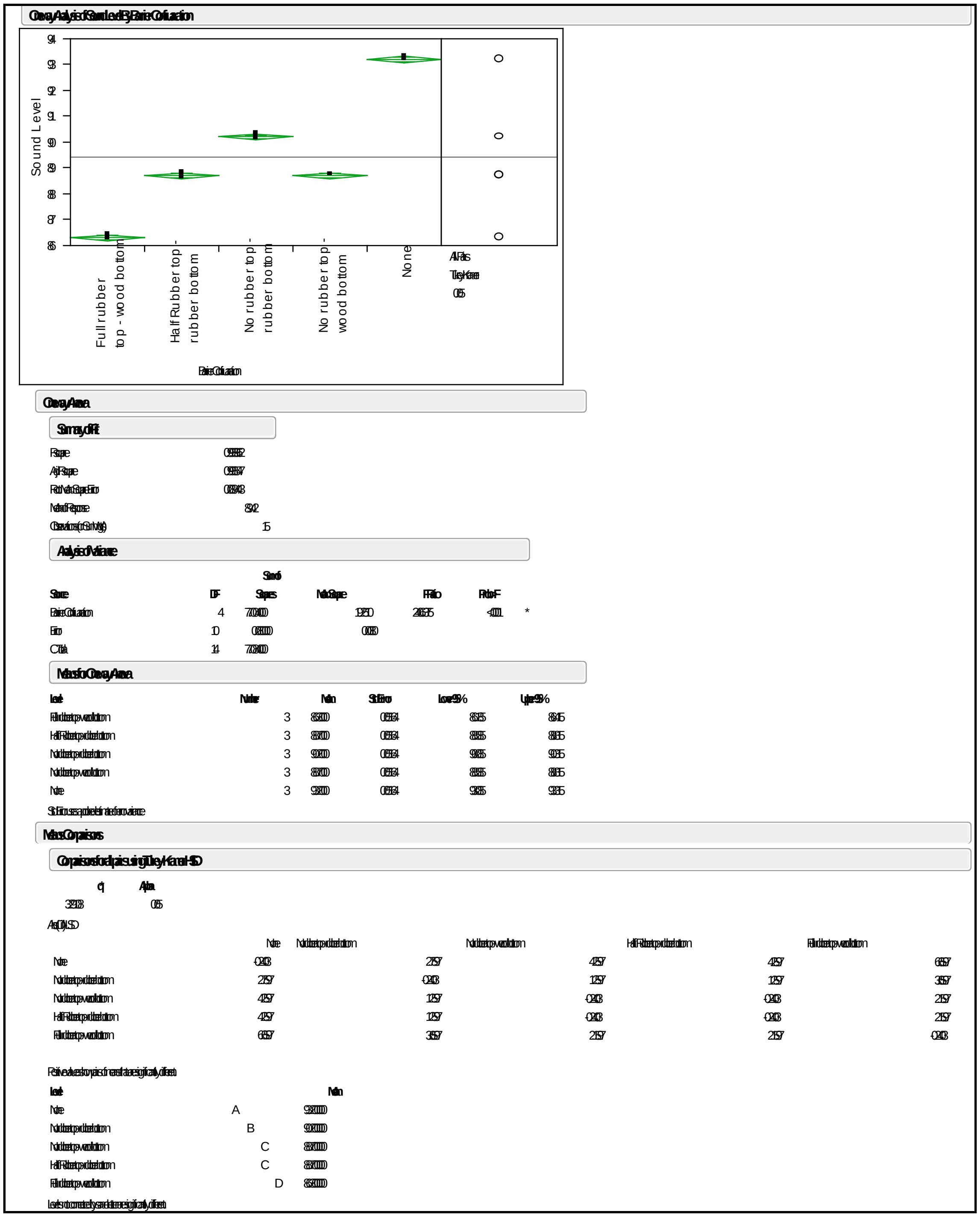
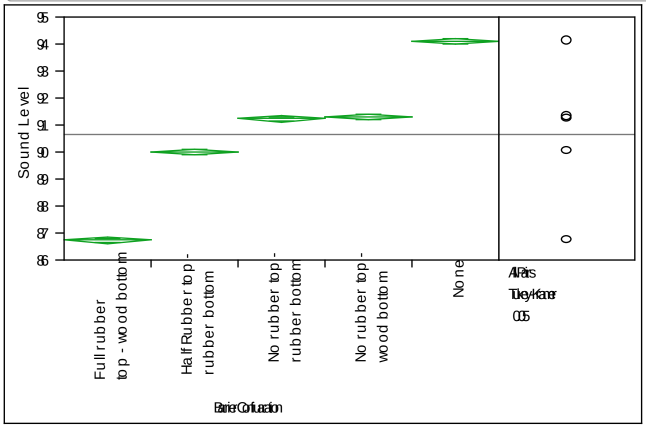


Figure C 7: Oneway analysis of sound level by barrier configuration sound type=pink, position=headgate, operator height=high

Oneway Analysis of Sound Level By Barrier Configuration



Oneway Anova

Summary of Fit

Rsquare	0.998907
Adj Rsquare	0.998469
Root Mean Square Error	0.096609
Mean of Response	90.67333
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F	
Barrier Configuration	4	85.276000	21.3190	2284.179	<.0001	*
Error	10	0.093333	0.0093			
C Total	14	85.369333				

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Full rubber top - wood bottom	3	86.7333	0.05578	86.609	86.858
Half Rubber top - rubber bottom	3	90.0000	0.05578	89.876	90.124
No rubber top - rubber bottom	3	91.2333	0.05578	91.109	91.358
No rubber top - wood bottom	3	91.3000	0.05578	91.176	91.424
None	3	94.1000	0.05578	93.976	94.224

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
3.29108	0.05

Abs(Dif)-LSD

	None	No rubber top - wood bottom	No rubber top - rubber bottom	Half Rubber top - rubber bottom	Full rubber top - wood bottom
None	-0.256	2.544	2.611	3.844	7.111
No rubber top - wood bottom	2.544	-0.256	-0.189	1.044	4.311
No rubber top - rubber bottom	2.611	-0.189	-0.256	0.977	4.244
Half Rubber top - rubber bottom	3.844	1.044	0.977	-0.256	3.011
Full rubber top - wood bottom	7.111	4.311	4.244	3.011	-0.256

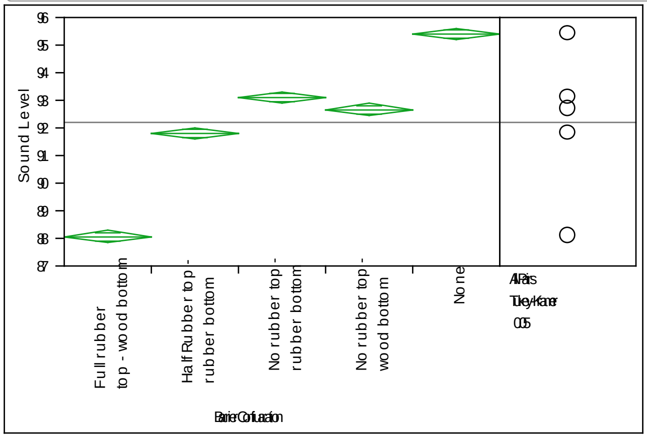
Positive values show pairs of means that are significantly different.

Level					Mean
None	A				94.100000
No rubber top - wood bottom		B			91.300000
No rubber top - rubber bottom		B			91.233333
Half Rubber top - rubber bottom			C		90.000000
Full rubber top - wood bottom				D	86.733333

Levels not connected by same letter are significantly different.

Figure C 8: Oneway analysis of sound level by barrier configuration sound type=pink, position=tailgate, operator height=low

Oneway Analysis of Sound Level By Barrier Configuration



Oneway Anova

Summary of Fit

RSquare	0.996815
Adj RSquare	0.995541
Root Mean Square Error	0.165328
Mean of Response	92.20667
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F	
Barrier Configuration	4	85.536000	21.3840	782.3415	<.0001	*
Error	10	0.273333	0.0273			
C. Total	14	85.809333				

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Full rubber top-wood bottom	3	88.0667	0.09545	87.854	88.279
Half Rubber top-rubber bottom	3	91.8000	0.09545	91.587	92.013
No rubber top-rubber bottom	3	93.1000	0.09545	92.887	93.313
No rubber top-wood bottom	3	92.6667	0.09545	92.454	92.879
None	3	95.4000	0.09545	95.187	95.613

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
3.29108	0.05

Abs(Dif)-LSD

	None	No rubber top-rubber bottom	No rubber top-wood bottom	Half Rubber top-rubber bottom	Full rubber top-wood bottom
None	-0.4443	1.8557	2.2891	3.1557	6.8891
No rubber top-rubber bottom	1.8557	-0.4443	-0.0109	0.8557	4.5891
No rubber top-wood bottom	2.2891	-0.0109	-0.4443	0.4224	4.1557
Half Rubber top-rubber bottom	3.1557	0.8557	0.4224	-0.4443	3.2891
Full rubber top-wood bottom	6.8891	4.5891	4.1557	3.2891	-0.4443

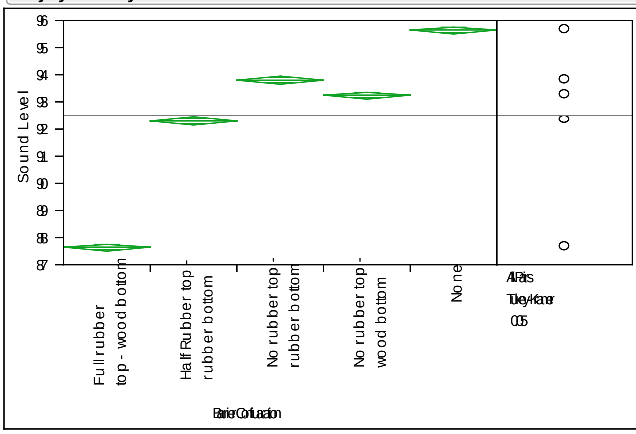
Positive values show pairs of means that are significantly different.

Level					Mean
None	A				95.400000
No rubber top-rubber bottom		B			93.100000
No rubber top-wood bottom		B			92.666667
Half Rubber top-rubber bottom			C		91.800000
Full rubber top-wood bottom				D	88.066667

Levels not connected by same letter are significantly different.

Figure C 9: Oneway analysis of sound level by barrier configuration sound type=pink, position=tailgate, operator height=medium

Oneway Analysis of Sound Level By Barrier Configuration



Oneway Anova

Summary of Fit

Rsquare	0.998883
Adj Rsquare	0.998436
Root Mean Square Error	0.109545
Mean of Response	92.52
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F	
Barrier Configuration	4	107.30400	26.8260	2235.500	<.0001	*
Error	10	0.12000	0.0120			
C. Total	14	107.42400				

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Full rubber top-wood bottom	3	87.6333	0.06325	87.492	87.774
Half Rubber top-rubber bottom	3	92.3000	0.06325	92.159	92.441
No rubber top-rubber bottom	3	93.8000	0.06325	93.659	93.941
No rubber top-wood bottom	3	93.2333	0.06325	93.092	93.374
None	3	95.6333	0.06325	95.492	95.774

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
3.29108	0.05

Abs(Dif)-LSD

	None	No rubber top-rubber bottom	No rubber top-wood bottom	Half Rubber top-rubber bottom	Full rubber top-wood bottom
None	-0.2944	1.5390	2.1056	3.0390	7.7056
No rubber top-rubber bottom	1.5390	-0.2944	0.2723	1.2056	5.8723
No rubber top-wood bottom	2.1056	0.2723	-0.2944	0.6390	5.3056
Half Rubber top-rubber bottom	3.0390	1.2056	0.6390	-0.2944	4.3723
Full rubber top-wood bottom	7.7056	5.8723	5.3056	4.3723	-0.2944

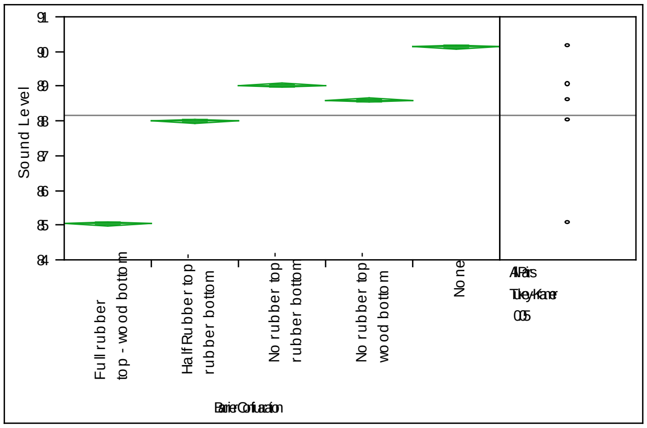
Positive values show pairs of means that are significantly different.

Level		Mean
None	A	95.633333
No rubber top-rubber bottom	B	93.800000
No rubber top-wood bottom	C	93.233333
Half Rubber top-rubber bottom	D	92.300000
Full rubber top-wood bottom	E	87.633333

Levels not connected by same letter are significantly different.

Figure C 10: Oneway analysis of sound level by barrier configuration sound type=pink, position=tailgate, operator height=high

Oneway Analysis of Sound Level By Barrier Configuration



Oneway Anova

Summary of Fit

Rsquare	0.999545
Adj Rsquare	0.999363
Root Mean Square Error	0.044721
Mean of Response	88.16
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F	
Barrier Configuration	4	43.956000	10.9890	5494.500	<.0001	*
Error	10	0.020000	0.0020			
C. Total	14	43.976000				

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Full rubber top-wood bottom	3	85.0333	0.02582	84.976	85.091
Half Rubber top-rubber bottom	3	88.0000	0.02582	87.942	88.058
No rubber top-rubber bottom	3	89.0333	0.02582	88.976	89.091
No rubber top-wood bottom	3	88.6000	0.02582	88.542	88.658
None	3	90.1333	0.02582	90.076	90.191

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
3.29108	0.05

Abs(Dif)-LSD

	None	No rubber top-rubber bottom	No rubber top-wood bottom	Half Rubber top-rubber bottom	Full rubber top-wood bottom
None	-0.1202	0.9798	1.4132	2.0132	4.9798
No rubber top-rubber bottom	0.9798	-0.1202	0.3132	0.9132	3.8798
No rubber top-wood bottom	1.4132	0.3132	-0.1202	0.4798	3.4465
Half Rubber top-rubber bottom	2.0132	0.9132	0.4798	-0.1202	2.8465
Full rubber top-wood bottom	4.9798	3.8798	3.4465	2.8465	-0.1202

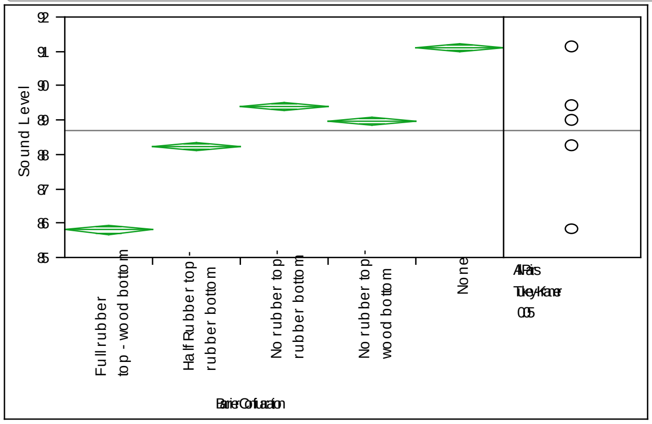
Positive values show pairs of means that are significantly different.

Level		Mean
None	A	90.133333
No rubber top-rubber bottom	B	89.033333
No rubber top-wood bottom	C	88.600000
Half Rubber top-rubber bottom	D	88.000000
Full rubber top-wood bottom	E	85.033333

Levels not connected by same letter are significantly different.

Figure C 11: Oneway analysis of sound level by barrier configuration sound type=recorded, position=center, operator height=low

Oneway Analysis of Sound Level By Barrier Configuration



Oneway Anova

Summary of Fit

Rsquare	0.997923
Adj Rsquare	0.997092
Root Mean Square Error	0.096609
Mean of Response	88.7
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F	
Barrier Configuration	4	44.84667	11.2117	1201.250	<.0001	*
Error	10	0.093333	0.0093			
C Total	14	44.94000				

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Full rubber top - wood bottom	3	85.8000	0.05578	85.676	85.924
Half Rubber top - rubber bottom	3	88.2333	0.05578	88.109	88.358
No rubber top - rubber bottom	3	89.4000	0.05578	89.276	89.524
No rubber top - wood bottom	3	88.9667	0.05578	88.842	89.091
None	3	91.1000	0.05578	90.976	91.224

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
3.29108	0.05

Abs(Dif)-LSD

	None	No rubber top - rubber bottom	No rubber top - wood bottom	Half Rubber top - rubber bottom	Full rubber top - wood bottom
None	-0.2596	1.4404	1.8737	2.6071	5.0404
No rubber top - rubber bottom	1.4404	-0.2596	0.1737	0.9071	3.3404
No rubber top - wood bottom	1.8737	0.1737	-0.2596	0.4737	2.9071
Half Rubber top - rubber bottom	2.6071	0.9071	0.4737	-0.2596	2.1737
Full rubber top - wood bottom	5.0404	3.3404	2.9071	2.1737	-0.2596

Positive values show pairs of means that are significantly different.

Level		Mean
None	A	91.100000
No rubber top - rubber bottom	B	89.400000
No rubber top - wood bottom	C	88.966667
Half Rubber top - rubber bottom	D	88.233333
Full rubber top - wood bottom	E	85.800000

Levels not connected by same letter are significantly different.

Figure C 12: Oneway analysis of sound level by barrier configuration sound type=recorded, position=center, operator height=medium

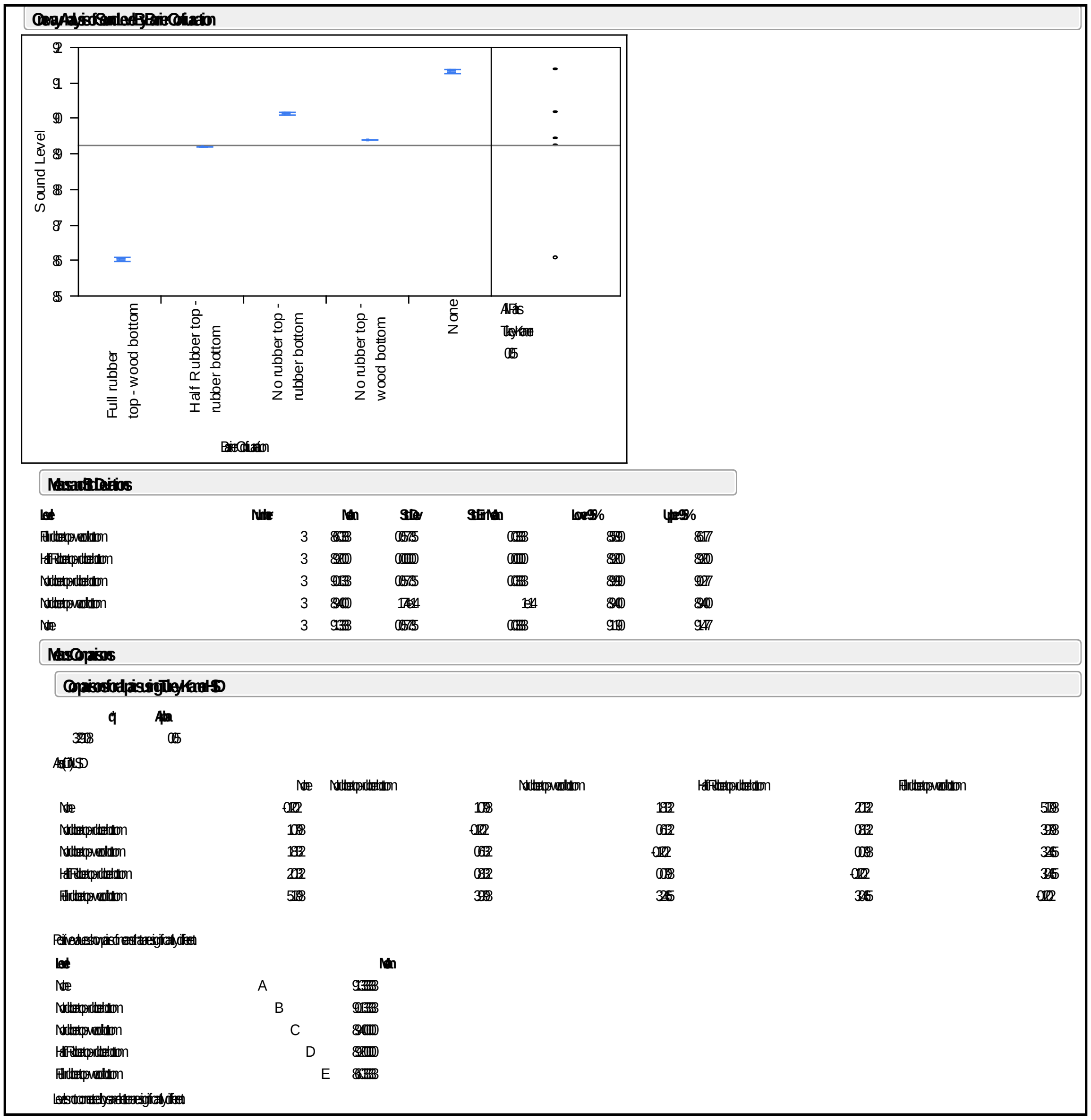
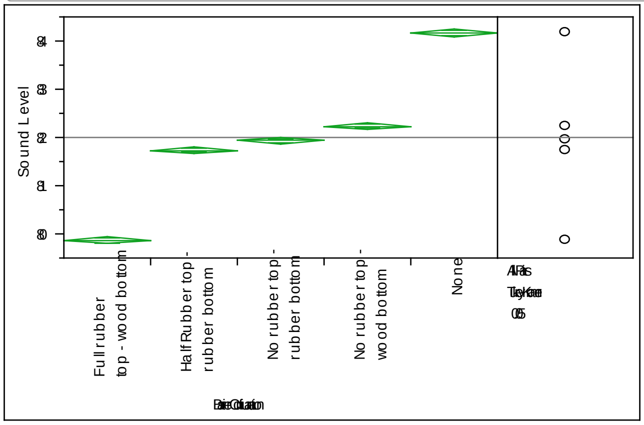


Figure C 13: Oneway analysis of sound level by barrier configuration sound type=recorded, position=center, operator height=high



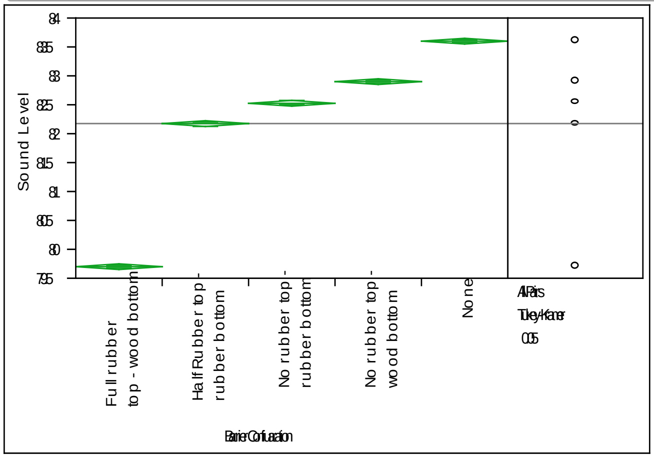
[illegible]	4	[illegible]	[illegible]	[illegible]	[illegible]	*
[illegible]	[illegible]	[illegible]	[illegible]			
[illegible]	[illegible]	[illegible]				

[illegible]	3	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	3	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	3	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	3	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	3	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]	A	[illegible]
[illegible]	B	[illegible]
[illegible]	C	[illegible]
[illegible]	D	[illegible]
[illegible]	E	[illegible]

Figure C 14: Oneway analysis of sound level by barrier configuration sound type=recorded, position=headgate, operator height=low

Oneway Analysis of Sound Level By Barrier Configuration



Oneway Anova

Summary of Fit

Rsquare	0.999496
Adj Rsquare	0.999294
Root Mean Square Error	0.036515
Mean of Response	82.18
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F	
Barrier Configuration	4	26.430667	6.60767	4955.750	<.0001	*
Error	10	0.013333	0.00133			
C. Total	14	26.444000				

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Full rubber top - wood bottom	3	79.7000	0.02108	79.653	79.747
Half Rubber top - rubber bottom	3	82.1667	0.02108	82.120	82.214
No rubber top - rubber bottom	3	82.5333	0.02108	82.486	82.580
No rubber top - wood bottom	3	82.9000	0.02108	82.853	82.947
None	3	83.6000	0.02108	83.553	83.647

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
3.29108	0.05

Abs(Dif)-LSD

	None	No rubber top - wood bottom	No rubber top - rubber bottom	Half Rubber top - rubber bottom	Full rubber top - wood bottom
None	-0.0981	0.6019	0.9685	1.3352	3.8019
No rubber top - wood bottom	0.6019	-0.0981	0.2685	0.6352	3.1019
No rubber top - rubber bottom	0.9685	0.2685	-0.0981	0.2685	2.7352
Half Rubber top - rubber bottom	1.3352	0.6352	0.2685	-0.0981	2.3685
Full rubber top - wood bottom	3.8019	3.1019	2.7352	2.3685	-0.0981

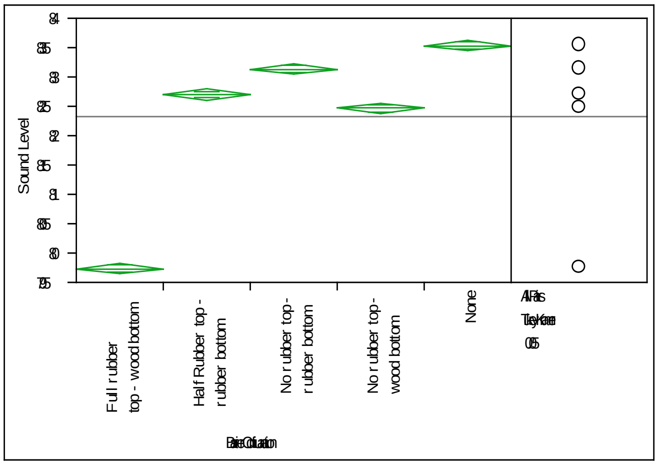
Positive values show pairs of means that are significantly different.

Level		Mean
None	A	83.600000
No rubber top - wood bottom	B	82.900000
No rubber top - rubber bottom	C	82.533333
Half Rubber top - rubber bottom	D	82.166667
Full rubber top - wood bottom	E	79.700000

Levels not connected by same letter are significantly different.

Figure C 15: Oneway analysis of sound level by barrier configuration sound type=recorded, position=headgate, operator height=medium

Oneway Analysis of Sound Level By Barrier Configuration



Oneway Anova

Summary of Fit

Rsquare	[illegible]
Adj Rsquare	[illegible]
Root Mean Square Error	[illegible]
Mean of Response	[illegible]
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Barrier Configuration	4	[illegible]	[illegible]	[illegible]	[illegible] *
Error	10	[illegible]	[illegible]		
C. Total	14	[illegible]			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Full rubber top - wood bottom	3	[illegible]	[illegible]	[illegible]	[illegible]
Half Rubber top - rubber bottom	3	[illegible]	[illegible]	[illegible]	[illegible]
No rubber top - rubber bottom	3	[illegible]	[illegible]	[illegible]	[illegible]
No rubber top - wood bottom	3	[illegible]	[illegible]	[illegible]	[illegible]
None	3	[illegible]	[illegible]	[illegible]	[illegible]

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
[illegible]	[illegible]

Abs(Dif)-LSD

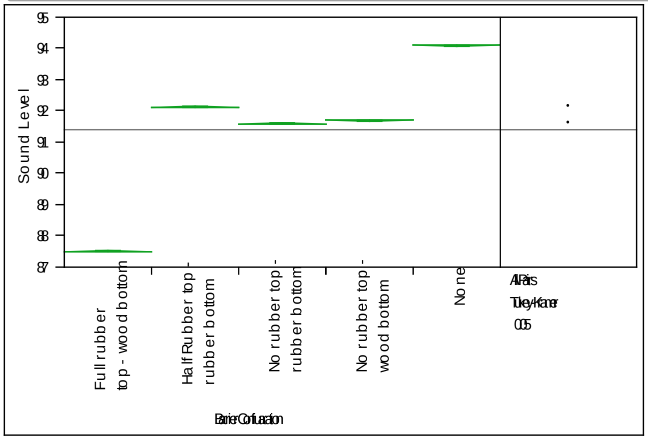
	None	No rubber top - rubber bottom	Half Rubber top - rubber bottom	No rubber top - wood bottom	Full rubber top - wood bottom
None	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
No rubber top - rubber bottom	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Half Rubber top - rubber bottom	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
No rubber top - wood bottom	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Full rubber top - wood bottom	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Positive values show pairs of means that are significantly different.

Level		Mean
None	A	[illegible]
No rubber top - rubber bottom	B	[illegible]
Half Rubber top - rubber bottom	C	[illegible]
No rubber top - wood bottom	D	[illegible]
Full rubber top - wood bottom	E	[illegible]

Figure C 16: Oneway analysis of sound level by barrier configuration sound type=recorded, position=headgate, operator height=high

Oneway Analysis of Sound Level By Barrier Configuration



Oneway Anova

Summary of Fit

Rsquare	0.999904
Adj Rsquare	0.999866
Root Mean Square Error	0.02582
Mean of Response	91.40667
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F	
Barrier Configuration	4	69.50267	17.3757	26063.50	<.0001	*
Error	10	0.00667	0.000667			
C. Total	14	69.50933				

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Full rubber top-wood bottom	3	87.5000	0.01491	87.467	87.533
Half Rubber top-rubber bottom	3	92.1333	0.01491	92.100	92.167
No rubber top-rubber bottom	3	91.6000	0.01491	91.567	91.633
No rubber top-wood bottom	3	91.7000	0.01491	91.667	91.733
None	3	94.1000	0.01491	94.067	94.133

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
3.29108	0.05

Abs(Dif)-LSD

	None	Half Rubber top-rubber bottom	No rubber top-wood bottom	No rubber top-rubber bottom	Full rubber top-wood bottom
None	-0.0694	1.8973	2.3306	2.4306	6.5306
Half Rubber top-rubber bottom	1.8973	-0.0694	0.3640	0.4640	4.5640
No rubber top-wood bottom	2.3306	0.3640	-0.0694	0.0306	4.1306
No rubber top-rubber bottom	2.4306	0.4640	0.0306	-0.0694	4.0306
Full rubber top-wood bottom	6.5306	4.5640	4.1306	4.0306	-0.0694

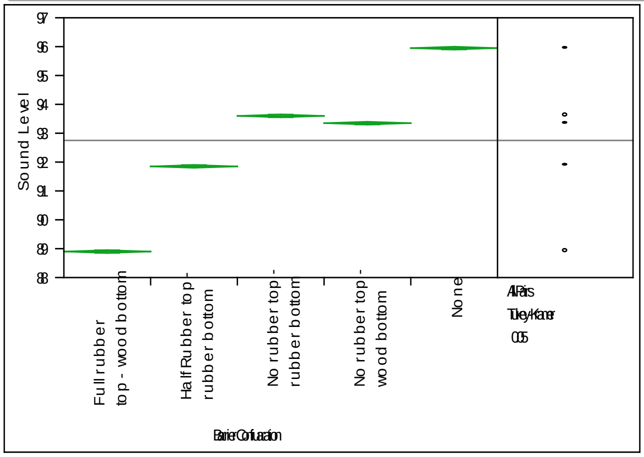
Positive values show pairs of means that are significantly different.

Level						Mean
None	A					94.100000
Half Rubber top-rubber bottom		B				92.133333
No rubber top-wood bottom			C			91.700000
No rubber top-rubber bottom				D		91.600000
Full rubber top-wood bottom					E	87.500000

Levels not connected by same letter are significantly different.

Figure C 17: Oneway analysis of sound level by barrier configuration sound type=recorded, position=tailgate, operator height=low

Oneway Analysis of Sound Level By Barrier Configuration



Oneway Anova

Summary of Fit

Rsquare	0.999751
Adj Rsquare	0.999652
Root Mean Square Error	0.044721
Mean of Response	92.72667
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F	
Barrier Configuration	4	80.389333	20.0973	10048.67	<.0001	*
Error	10	0.020000	0.0020			
C. Total	14	80.409333				

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Full rubber top - wood bottom	3	88.9000	0.02582	88.842	88.958
Half Rubber top - rubber bottom	3	91.8667	0.02582	91.809	91.924
No rubber top - rubber bottom	3	93.6000	0.02582	93.542	93.658
No rubber top - wood bottom	3	93.3333	0.02582	93.276	93.391
None	3	95.9333	0.02582	95.876	95.991

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
3.29108	0.05

Abs(Dif)-LSD

	None	No rubber top - rubber bottom	No rubber top - wood bottom	Half Rubber top - rubber bottom	Full rubber top - wood bottom
None	-0.1202	2.2132	2.4798	3.9465	6.9132
No rubber top - rubber bottom	2.2132	-0.1202	0.1465	1.6132	4.5798
No rubber top - wood bottom	2.4798	0.1465	-0.1202	1.3465	4.3132
Half Rubber top - rubber bottom	3.9465	1.6132	1.3465	-0.1202	2.8465
Full rubber top - wood bottom	6.9132	4.5798	4.3132	2.8465	-0.1202

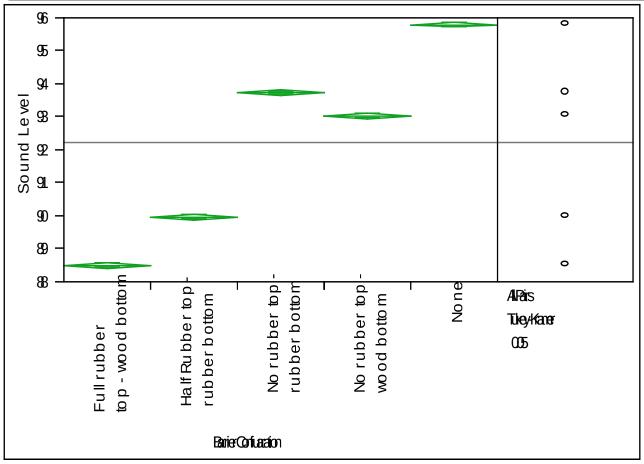
Positive values show pairs of means that are significantly different.

Level		Mean
None	A	95.933333
No rubber top - rubber bottom	B	93.600000
No rubber top - wood bottom	C	93.333333
Half Rubber top - rubber bottom	D	91.866667
Full rubber top - wood bottom	E	88.900000

Levels not connected by same letter are significantly different.

Figure C 18: Oneway analysis of sound level by barrier configuration sound type=recorded, position=tailgate, operator height=medium

Oneway Analysis of Sound Level By Barrier Configuration



Oneway Anova

Summary of Fit

Rsquare	0.99616
Adj Rsquare	0.99462
Root Mean Square Error	0.06324
Mean of Response	92.20667
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Barrier Configuration	4	104.0493	26.0123	6503.083	<.0001 *
Error	10	0.04000	0.0040		
C. Total	14	104.0893			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Full rubber top-wood bottom	3	88.5000	0.03651	88.419	88.581
Half Rubber top-rubber bottom	3	89.9667	0.03651	89.885	90.048
No rubber top-rubber bottom	3	93.7333	0.03651	93.652	93.815
No rubber top-wood bottom	3	93.0333	0.03651	92.952	93.115
None	3	95.8000	0.03651	95.719	95.881

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
3.29108	0.05

Abs(Dif)-LSD

	None	No rubber top-rubber bottom	No rubber top-wood bottom	Half Rubber top-rubber bottom	Full rubber top-wood bottom
None	-0.1700	1.8967	2.5967	5.6634	7.1300
No rubber top-rubber bottom	1.8967	-0.1700	0.5300	3.5967	5.0634
No rubber top-wood bottom	2.5967	0.5300	-0.1700	2.8967	4.3634
Half Rubber top-rubber bottom	5.6634	3.5967	2.8967	-0.1700	1.2967
Full rubber top-wood bottom	7.1300	5.0634	4.3634	1.2967	-0.1700

Positive values show pairs of means that are significantly different.

Level		Mean
None	A	95.800000
No rubber top-rubber bottom	B	93.733333
No rubber top-wood bottom	C	93.033333
Half Rubber top-rubber bottom	D	89.966667
Full rubber top-wood bottom	E	88.500000

Levels not connected by same letter are significantly different.

Figure C 19: Oneway analysis of sound level by barrier configuration sound type=recorded, position=tailgate, operator height=high

Appendix D

The following decision matrix and barrier modeling can be used to help dtermine if a barrier can be ean effective engineering control

Decision Matrix		
1. Is a barrier physically possible?	Yes	Proceed to Question 2
2. Will the worker accept a barrier?	Yes	Proceed to Question 3
3. Is the hazard source stationary or semi-stationary?	Yes	Proceed to Question 4
4. Is this for noise or dust control?	Noise	Proceed to Question 5
5. Can the barrier be modeled?	Yes	Proceed to Modeling Sheet
6. Does model indicate a 3dB(A) reduciton or greater?	Yes	Test Barrier
7. Is cross ventilation available to channel dust away from ope	Yes	Test Barrier

NOTE: These Calculations assume a perfect barrier in a free field, the predicted sound reduction may be less than the observed
All Measurements must be input in meters

Area Data	
Height of Source (m)	1
Height of Receiver (m)	1.5
Height of Barrier (m)	2.4
Line of sight distance between source and receiver (m)	1.2
Height of ceiling (m)	3.6
Ceiling material (pick from dropdown)	Suspended Acoustical tile

Octave Band Measurement of Source									
Freqeuncy	31.5	63	125	250	500	1000	2000	4000	8000
Octave Band Measurement of Source	80.3	90.6	98.7	96.4	96.5	97.7	95.0	93.9	90.1

Results	
Calculated dB(A) without barrier	102
Calculated dB(A) with barrier	90
Reduction dB(A)	12

Figure D 1: WPAFB Headgate Position

The following decision matrix and barrier modeling can be used to help dtermine if a barrier can be ean effective engineering control

Decision Matrix		
1. Is a barrier physically possible?	Yes	Proceed to Question 2
2. Will the worker accept a barrier?	Yes	Proceed to Question 3
3. Is the hazard source stationary or semi-stationary?	Yes	Proceed to Question 4
4. Is this for noise or dust control?	Noise	Proceed to Question 5
5. Can the barrier be modeled?	Yes	Proceed to Modeling Sheet
6. Does model indicate a 3dB(A) reduciton or greater?	Yes	Test Barrier
7. Is cross ventilation available to channel dust away from ope	Yes	Test Barrier

NOTE: These Calculations assume a perfect barrier in a free field, the predicted sound reduction may be less than the observed
All Measurements must be input in meters

Area Data	
Height of Source (m)	1
Height of Receiver (m)	1.5
Height of Barrier (m)	2.4
Line of sight distance between source and receiver (m)	1.2
Height of ceiling (m)	3.6
Ceiling material (pick from dropdown)	Suspended Acoustical tile

Octave Band Measurement of Source									
Freqeuncy	31.5	63	125	250	500	1000	2000	4000	8000
Octave Band Measurement of Source	80.5	90.8	95.3	90.3	95.3	91.7	96.2	85.4	84.3

Results	
Calculated dB(A) without barrier	100
Calculated dB(A) with barrier	85
Reduction dB(A)	15

Figure D 2: WPAFB tailgate position

The following decision matrix and barrier modeling can be used to help dtermine if a barrier can be ean effective engineering control		
Decision Matrix		
1. Is a barrier physically possible?	Yes	Proceed to Question 2
2. Will the worker accept a barrier?	Yes	Proceed to Question 3
3. Is the hazard source stationary or semi-stationary?	Yes	Proceed to Question 4
4. Is this for noise or dust control?	Noise	Proceed to Question 5
5. Can the barrier be modeled?	Yes	Proceed to Modeling Sheet
6. Does model indicate a 3dB(A) reduciton or greater?	Yes	Test Barrier
7. Is cross ventilation available to channel dust away from ope	Yes	Test Barrier

NOTE: These Calculations assume a perfect barrier in a free field, the predicted sound reduction may be less than the observed
All Measurements must be input in meters

Area Data	
Height of Source (m)	1
Height of Receiver (m)	1.6
Height of Barrier (m)	2.4
Line of sight distance between source and receiver (m)	3.9
Height of ceiling (m)	3
Ceiling material (pick from dropdown)	Plywood

Octave Band Measurement of Source									
Freqeuncy	31.5	63	125	250	500	1000	2000	4000	8000
Octave Band Measurement of Source	73.7	90.1	94.5	93.0	95.5	90.0	86.1	81.3	78.6

Results	
Calculated dB(A) without barrier	96
Calculated dB(A) with barrier	93
Reduction dB(A)	2.9

Figure D 3: NIOSH-PRL headgate position, 50% male, barrier configuration D

The following decision matrix and barrier modeling can be used to help dtermine if a barrier can be ean effective engineering control		
Decision Matrix		
1. Is a barrier physically possible?	Yes	Proceed to Question 2
2. Will the worker accept a barrier?	Yes	Proceed to Question 3
3. Is the hazard source stationary or semi-stationary?	Yes	Proceed to Question 4
4. Is this for noise or dust control?	Noise	Proceed to Question 5
5. Can the barrier be modeled?	Yes	Proceed to Modeling Sheet
6. Does model indicate a 3dB(A) reduciton or greater?	Yes	Test Barrier
7. Is cross ventilation available to channel dust away from ope	Yes	Test Barrier

NOTE: These Calculations assume a perfect barrier in a free field, the predicted sound reduction may be less than the observed
All Measurements must be input in meters

Area Data	
Height of Source (m)	1
Height of Receiver (m)	1.6
Height of Barrier (m)	2.4
Line of sight distance between source and receiver (m)	5.5
Height of ceiling (m)	3
Ceiling material (pick from dropdown)	Plywood

Octave Band Measurement of Source									
Freqeuncy	31.5	63	125	250	500	1000	2000	4000	8000
Octave Band Measurement of Source	82.9	91.8	91.1	90.7	90.8	83.5	81.8	77.8	71.1

Results	
Calculated dB(A) without barrier	91
Calculated dB(A) with barrier	89
Reduction dB(A)	1.8

Figure D 4: NIOSH-PRL center position, 50% male, barrier configuration D

The following decision matrix and barrier modeling can be used to help dtermine if a barrier can be ean effective engineering control

Decision Matrix		
1. Is a barrier physically possible?	Yes	Proceed to Question 2
2. Will the worker accept a barrier?	Yes	Proceed to Question 3
3. Is the hazard source stationary or semi-stationary?	Yes	Proceed to Question 4
4. Is this for noise or dust control?	Noise	Proceed to Question 5
5. Can the barrier be modeled?	Yes	Proceed to Modeling Sheet
6. Does model indicate a 3dB(A) reduciton or greater?	Yes	Test Barrier
7. Is cross ventilation available to channel dust away from op	Yes	Test Barrier

NOTE: These Calculations assume a perfect barrier in a free field, the predicted sound reduction may be less than the observed
All Measurements must be input in meters

Area Data	
Height of Source (m)	1
Height of Receiver (m)	1.6
Height of Barrier (m)	2.4
Line of sight distance between source and receiver (m)	3.3
Height of ceiling (m)	3
Ceiling material (pick from dropdown)	Plywood

Octave Band Measurement of Source									
Freqeuncy	31.5	63	125	250	500	1000	2000	4000	8000
Octave Band Measurement of Source	77.0	94.9	93.6	78.4	80.6	74.8	76.0	73.5	71.5

Results	
Calculated dB(A) without barrier	84
Calculated dB(A) with barrier	81
Reduction dB(A)	3.2

Figure D 5: NIOSH-PRL tailgate position, 50% male, barrier configuration D

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Vita

Captain Daniel D. Sweeney graduated from Helix High School in La Mesa, California in 1984. After high school, then Airmen Basic Sweeney enlisted into the Air Force (AF) and was a technical school Honor Graduate as an Aerospace Control and Warning Systems Operator. After four years of service, he separated from the AF.

Captain Sweeney graduated from the University of California at San Diego in 1997 with a Bachelor of Science degree in bioengineering. During this time, he was on the Provost's list for academic excellence nearly every quarter of attendance. After graduation, Capt Sweeney worked as a research assistant at The Scripps Research Institute. After this, he worked for Dura Pharmaceuticals in San Diego, California in the test development section working on a dry-powder form of insulin to treat diabetics.

Captain Sweeney received a direct commission into the AF in 1999 as a Bioenvironmental Engineer (BE). He received the Hoyt S. Vandenberg Award for Academic Excellence during commissioned officer training. His first duty assignment was at McChord AFB, Washington, where he received the AF Chief of Safety Medical Achievement Award. His next duty assignment was the BE element chief at Lajes Field, Azores, Portugal. Following the Azores, Capt Sweeney became the BE Branch Chief at Buckley AFB, Colorado. During this time, Capt Sweeney won the overall AF Grand Champion at the first ever AF chemical, biological, radiological, and nuclear response challenge. He was also the Air Force Space Command (AFSPC) 2005 Company Grade Officer (CGO) BE of the Year, the 460th Medical Group CGO of the Year, a two time recipient of the AFSPC BE flight of the year, and 17 additional wing or group awards for his element.

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14. ABSTRACT
The United States Air Force (USAF) has experienced a dramatic increase in hearing loss claims since 2001. Additionally, many operations within the USAF expose personnel to hazardous dust levels. Likewise, the US mining industry has difficulties controlling hazardous noise and dust exposures in underground mining. Specifically, studies have shown that coal mine longwall shearer operators are routinely exposed to noise levels at 151 percent of the allowable dose and approximately 20 percent exceed regulatory dust levels. An above ground full scale model of the underground shearing operation was developed to test the feasibility of mounting a permanent partial barrier on the longwall shearer. The barrier was constructed and tested at the National Institute for Occupational Safety and Health Pittsburgh Research Laboratory (NIOSH-PRL) longwall test facility. The barrier achieved as high as a 7.3 dB(A) reduction in noise levels and a 96 percent reduction in respirable dust. Several predictive models were tested and compared to measured noise reduction results. A final spreadsheet was developed as a tool for base level Bioenvironmental Engineers to determine when a partial barrier may be an effective engineering for controlling hazardous noise or dust within USAF industrial operations.

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